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Physiological Assessment of Ground Troops
under Thermal Stress Associated with Desert Warfare

Final Report
(July 1978 - July 1980)

Yair Shapiro, M.D.

July 31, 1980

Supported by

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19. KEY WORDS *(Continue on reverse side if necessary and identify by block number)* Sex-related differences; humid and dry heat; maximal oxygen uptake; body weight; skin surface area; body fat percentage; surface area-to-mass ratio; rectal temperature, mean skin temperature; sweat loss; sweat suppression; thermoregulatory set point; heat transfer; heat conductance; evaporative cooling; convection; radiation; metabolic heat production; acclimation; acclimatization; maximal		

20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

Sex-related differences in acclimation and thermal regulation was studied in nine female and ten male volunteer subjects. The subjects were exposed to a variety of hot-dry (HD) and hot-wet (HW) conditions. It was found that basically males and females acclimate in the same mechanism; the thermal regulatory set point of females in HD is higher than in males; females tolerate HW conditions better; females conserve better body water in HW by suppressing the non-evaporative sweat loss.

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Thirty-four males and nine females were exposed to a variety of environments, clothing and exercise combinations in order to develop an equation for predicting sweat loss. It was found that for the males, the sweat loss equalled:

$$\text{Male - sweat loss} = 28 \cdot E_{req} \cdot (E_{max})^{-0.45} ; g \cdot m^{-2} \cdot h^{-1}$$

$$\text{Female - sweat loss} = 15 \cdot E_{req} \cdot (E_{max})^{-0.36} ; g \cdot m^{-2} \cdot h^{-1}$$

where: E_{req} is the evaporative rate needed for thermal regulation and E_{max} is the maximal evaporative cooling of the environment.

Eight volunteer soldiers were acclimated twice to HD environments at the end of the summer and at the end of the winter. It was found that the winter thermal regulatory set point is higher than the summer; this difference cannot be eliminated by acclimation. The acclimation produced hemodilution, both in winter and summer while in the winter the volume expansion was both of plasma and red cell volume and during the summer, only the plasma volume was expanded.

A Monarch bicycle ergometer was modified for underwater exercise by removing the friction belt and mounting 1-6 fins on the fly-wheel. The modified ergometer was physiologically calibrated for the different combinations for pedalling speed, etc.

19. Keywords (Cont'd)

evaporative capacity; clothing insulation and permeability; bicycle ergometry pedalling rate; water immersion exercise; blood volume; plasma volume; seasonal variations.

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SUMMARY

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FORWARD

The objective of this grant was to conduct research investigations into the physiological responses and thermal limits of soldiers under conditions of thermal stress associated with desert warfare.

Evaluation of work performance included problem identificat·on and definition, formulation of research hypotheses, literature reviews, the planning and execution of research studies, analysis and interpretation of data, and preparation of these findings for publication in the open literature.

The grantee served as principal investigator on the following three major research studies: (1) Sex differences in heat tolerance and acclimatization, ME-3-78; (2) Prediction of sweat rate and heat tolerance, ME-4-78; and (3) Artificial heat acclimatization differences between cold and warm seasons, ME-5-78. The grantee also served as co-investigator on the following research studies: (1) Additive effects of solar and metabolic heat load in predicting heat intolerance, ME-7-76; (2) Comparison of eccentric and concentric muscle contractions during various types of work, ME-1-79; (3) Troop mobility of men and women as a function of load and terrain, ME-2-79; and (4) The effect of physical training in air or water in heat tolerance, ME-1-80.

The six resultant manuscripts from the above research efforts serve as the grantee's final products of his grant.

It is also to be further noted that general consultation in the areas of heat tolerance in soldiers was provided by the grantee to Institute staff as required.

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Modification of the Monarch bicycle ergometer for under-water exercise

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SEX DIFFERENCES IN ACCLIMATION TO A HOT-DRY ENVIRONMENT

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Running Head: Heat Acclimation of Men and Women

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ABSTRACT

Sex-related differences in acclimation to a hot-dry environment were evaluated in 10 males and 9 females. The subjects were exposed during early spring to a hot-dry climate: $49^{\circ}C$, 20% rh for 6 consecutive days. Exposures lasted 120 min: 10 min rest, 50 min walk ($1.34 \, m \cdot s^{-1}$), 10 min rest, 50 min walk. Heart rate, rectal temperature (T_{re}), mean skin temperature ($\overline{T}_{sk}$), and heat storage dropped significantly for both sexes ($P < 0.05$) from the 1st to the 6th day, with no significant changes ($P > 0.05$) between the last two days. In spite of similar metabolic rates, similar sweat rate and lower heat gain by radiation and convection for the females, their T_{re} and $\overline{T}_{sk}$ remained significantly higher ($P < 0.05$) than those for the males at the end of acclimation. It was suggested that the thermoregulatory set-point is higher for unacclimated women than for men, and that this difference does not disappear with acclimation.

INTRODUCTION

Acclimation is defined as "a physiological change, occurring within the life-time of an organism, which reduces the strain caused by experimentally induced stressful changes in particular climatic factors" (Bligh and Johnson 1973). Acclimation to heat is characterized by a smaller rise in rectal temperature (T_{re}), mean skin temperature ($\bar{T}_{sk}$) and heart rate (HR), and therefore more effective and prolonged tolerance during heat exposure (Wyndham 1973). The main physiological mechanisms involved in acclimation are an earlier onset of sweating, greater sweat sensitivity (lower thermoregulatory set-point) and expanded plasma volume (Bonner et al. 1976, Wyndham 1973).

Many studies indicate that females acclimate to heat successfully, showing a broadly similar pattern as compared to men (Bar-Or et al. 1969, Cleland et al. 1969, Fein et al. 1975, Hertig et al. 1963, Nunneley 1978, Weinman et al. 1967, Wyndham et al. 1965), but despite this similarity some of these studies showed that the females achieved lower levels of acclimation (Cleland et al. 1969, Fein et al. 1975, Hertig et al. 1963) or a slower rate of acclimation (Wyndham et al. 1965). Bar-Or et al. (1969) showed no sex-related differences in acclimation, while Weinman et al. (1967) showed better acclimation for the females.

A recent study showed that while the basic thermal physiology for men and women is similar, the major sex differences are a higher surface area to mass ratio for the females which helps them to dissipate heat in hot-wet environments, and a higher thermoregulatory set-point for the women under hot-dry conditions (Shapiro et al. 1980). The latter observation might raise questions as to whether this higher thermoregulatory set-point is a result of a lesser ability to reach a high level of acclimation, or whether a real sex difference exists in any

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state of heat acclimation regardless of the level of acclimation. The purpose of this study was to compare heat acclimation to hot-dry conditions between the sexes in terms of rate, level, heat balance and heat transfer.

METHODS

Nine female and 10 male soldiers served as volunteer subjects. All subjects were totally informed with regard to experimental risk and gave their written informed consent. The physical characteristics of the subjects are summarized in Table 1. All experiments were conducted during early spring and none of the subjects had been exposed to environmental temperatures higher than $24^{\circ}C$ for five months prior to the study.

Prior to the heat exposures, all subjects underwent medical examination, anthropometric measurements (height, weight, skinfold thickness) and determination of maximal oxygen uptake ($\dot{V}O_2$ max). Maximal oxygen uptake was determined from an intermittent treadmill running test utilizing methods and techniques modified from Taylor et al. (1955). During these tests, expired air was collected in Douglas bags; the volume was measured in a Collins Spirometer and converted to standard environmental conditions (STPD); and the O_2 and CO_2 concentrations were measured with an Applied Electrochemistry Model S-3A O_2 analyzer and Beckman LB-2 infrared CO_2 analyzer. Heart rate was calculated from R-R (ECG) intervals recorded on a Hewlett-Packard Model 1511A Electrocardiograph.

The nineteen male and female subjects, dressed in T-shirts, shorts, socks and indoor shoes, were then concurrently acclimated for 6 consecutive days by walking on a level motor-driven treadmill at $1.34 \, m \cdot s^{-1}$ at $49^{\circ}C$, 20% rh,

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$1 \text{ m} \cdot \text{s}^{-1}$ wind speed. Each of these six exposures lasted 120 min: 10' rest, 50' walk, 10' rest, 50' walk. At the end of the first rest period and at the end of each walking period, two-minute expired air samples were collected in Douglas bags and analyzed as previously described for calculation of metabolic rate (M).

During all heat exposures, rectal temperature (T_{re}) was recorded from a Y.S.I. rectal thermistor probe inserted ~ 10 cm beyond the anal sphincter. Skin temperatures were monitored with a three-point thermocouple skin harness (chest, calf and forearm) and mean weighted skin temperature ($\bar{T}_{sk}$) was calculated according to Burton (1935). Using a Hewlett Packard 9825A Calculator and 9862A Plotter on-line during experimentation, both $\bar{T}_{sk}$ and T_{re} were plotted for each subject at approximately 2-min intervals. Heat storage (ΔS) was calculated as follows: $\Delta S = 0.965 (0.8 \Delta T_{re} + 0.2 \Delta \bar{T}_{sk})$ in $\text{W} \cdot \text{kg}^{-1}$ (Hardy 1961). Heart rate was measured by radial artery palpation during the rest periods and after each 25 min of walking. Ad lib drinking of water was encouraged. Total body weight losses were determined from pre- and post-walk measurements on a K-120 Sauter precision electronic balance (accuracy of ± 10 g) for calculation of sweat rate. Sweat rate ($\dot{m}_{sw}$) was determined by loss of weight adjusted for water intake, urine output, and respiratory and metabolic weight losses. Respiratory weight loss ($\dot{m}_e$) was calculated as: $\dot{m}_e = 0.019 \dot{V}O_2$ $(44 - P_a)$ in $\text{g} \cdot \text{min}^{-1}$, and metabolic weight loss ($\dot{m}_r$) as: $\dot{m}_r = 0.53 \dot{V}O_2$ in $\text{g} \cdot \text{min}^{-1}$, where $\dot{V}O_2$ is the oxygen uptake in $\text{l} \cdot \text{min}^{-1}$ (STPD) and P_a is the ambient water pressure in mm Hg (Mitchell et al. 1972). The heat gain by radiation and convection (R + C) was determined according to Givoni and Goldman (1972). Sweat evaporative heat loss (E_{sw}) was calculated as: $E_{sw} = M + (R + C) - \Delta S - E_{res}$, where E_{res} is the respiratory heat loss calculated as $E_{res} = 0.0023 M (44 - P_a)$ (Mitchell et al. 1972). The $\Delta (T_{re} - \bar{T}_{sk})$ was

determined as an average value from each of the two-minute values. Conductance (h_k) was determined as: $h_k = (M - \Delta S)/(T_{re} - \bar{T}_{sk})$ in $W \cdot m^{-2} \cdot {}^{o}C^{-1}$ (Nadel 1972).

Statistical treatment

Most variables were evaluated by use of a mixed design of two factors, with one factor being the two groups (male and female) and the other being the treatment (number of days in the heat) which both groups received. If a significant F-value was found (P < 0.05), critical differences were analyzed by Tukey's procedure to locate the significant mean differences.

RESULTS

During the six days of heat acclimation, metabolic rate and $\dot{m}_{sw}$ remained unchanged and similar for both sexes. (see Figure 1 and Table 2). During acclimation, final heart rate dropped 30.0 $b \cdot min^{-1}$ for males and 27.2 for the females (P < 0.001) as illustrated in Figure 2. Figure 3 shows that final T_{re} dropped $0.46^{o}C$ for the males and $0.70^{o}C$ for the females (P < 0.001), while $\bar{T}_{sk}$ dropped $0.55^{o}C$ for the females and $0.37^{o}C$ for the males (P < 0.005) as presented in Table 2.

The heart rate showed a trend of higher values for the females than for the males, but this difference was not significant. The T_{re} and $\bar{T}_{sk}$ which were significantly higher for the women remained significantly higher after the heat acclimation period. The time change functions for HR and T_{re} were found to be:

males: $\quad T_{re} = 38.56 \exp(-0.003N)$, r = 0.96

$\quad\quad\quad\quad$ HR $= 153.1 \exp(-0.005N)$, r = 0.98

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females: T_{re} = 39.02 exp(-0.004N), r = 0.98

HR = 161.7 exp(-0.004N), r = 0.96

where N is number of days in the heat.

No significant changes were found for T_{re}, $\bar{T}_{sk}$ or HR between the last two days of acclimation for either sex. The ΔS dropped significantly (P < 0.01) during acclimation for both sexes (0.06 W • kg^{-1} for the males and 0.37 for the females), but was not significantly different between the sexes either before or after acclimation (see Table 2). Heat gain by radiation and convection (R + C) as well as heat loss by evaporation of sweat (E_{sw}) were significantly higher (P < 0.001) for the males than for the females for all days, but did not change during acclimation.

Despite a higher T_{re} to $\bar{T}_{sk}$ gradient for the males (1.54 $^{\circ}$C vs. 0.97 for females on the 1st day and 1.74 $^{\circ}$C for males vs. 1.31 for females on the last day), similar conductance was found for both sexes both before and after acclimation. None of the changes mentioned above were found to be correlated with maximal oxygen uptake ($\dot{V}O_2$ max).

DISCUSSION

The subjects in this study were pre-exposed only to environmental temperatures below 24°C, while the experimental temperature was 49°C. Thus, these subjects could be classified as unacclimated to the experimental conditions, such that their physiological reactions during the study could be considered as acclimation responses. It could also be suggested that the preacclimation conditions were relatively similar for both sexes.

The two major differences in terms of physical characteristics between males and females are the lower cardiorespiratory physical fitness for the

females (lower $\dot{V}O_2$ max), and their smaller body size (lower weight, height and skin surface area, and higher surface area to mass ratio). The importance of the latter was discussed in a previous article (Shapiro et al. 1980) where it was shown that body size, especially the surface area to mass ratio, played a major role in heat dissipation for females in hot-humid environments, but was not as important a factor in hot-dry environments. Lack of correlation between $\dot{V}O_2$ max and the thermoregulatory parameters discussed in this same study seemed to exclude the level of cardiorespiratory physical fitness as a major factor in the sex differences during acclimation.

Analyzing the T_{re}, $\bar{T}_{sk}$, ΔS and HR data illustrates that both sexes improved their thermoregulatory and cardiovascular responses during the acclimation. In contrast to Wyndham et al. (1965), who suggested that females acclimate slower, the present study shows that the rate of change of response was similar for both sexes ($e^{-0.003N}$ and $e^{-0.005N}$ for the males' T_{re} and HR; and, $e^{-0.004N}$ for the females' T_{re} and HR). These rates of change are in full agreement with those previously reported by Givoni and Goldman (1973) for other young male soldiers. All other heat balance and heat transfer parameters, i.e., M, R + C, E_{sw} and conductance, remained unchanged as expected during acclimation, and as was previously shown by Shapiro et al. (1980), R + C, (T_{re} - $\bar{T}_{sk}$) and evaporative heat loss were lower for the women than for the men when values were expressed per unit body surface area.

Sweat rate was basically unchanged in both sexes during acclimation (although there was a 5% increase for the males). These findings are in controversy with classical acclimation studies (Kuno, 1956) but might be explained by the particular hot-dry environment used to acclimate the subjects in the present study (Pandolf et al. 1977). During the first day of acclimation,

the females showed the same sweat rate, but lower evaporation rate than the males. On the other hand, the ratio between $\dot{m}_{sw}$ and E_{sw} on the last day of acclimation was the same for both sexes. These observations raise the question as to whether unacclimated women evaporate sweat less effectively than men. Neither the literature nor this study can elucidate this point and further study should be done to answer this question.

In spite of similar rates of achieving heat acclimation, the final rectal temperature and mean skin temperature remained higher for the females after acclimation as well as before acclimation. It is suggested that these differences are mainly due to a higher thermoregulatory set-point for the females, as was found in other studies (Roberts et al. 1977, Shapiro et al. 1980) both before and after acclimation.

The literature controversy about the sex-related differences in acclimation can be explained by differences in environmental conditions to which the sexes were acclimated and were tested before and after the acclimation. Weinman et al. (1967) showed that females acclimated better than males in their study under hot-wet conditions, which is an environment which might be expected to result in better thermoregulatory reactions for females (Shapiro et al. 1980). However, Bar-Or et al. (1969) and Hertig et al. (1963) acclimated their subjects to hot-dry conditions, and found higher post-acclimation T_{re} and/or $\bar{T}_{sk}$ values for the females, as was confirmed in the present study. Roberts et al. (1977), who acclimated their subjects to a hot-wet environment, but tested them both pre and post-acclimation in mild conditions ($25^{o}C$), showed the existence of differences in thermoregulatory set-point regardless of acclimation or physical training.

It can be concluded that males and females acclimate to a hot-dry environment at the same rate. The thermoregulatory set-point was higher for

the females than for the males both before and after acclimation. The pre-acclimation sex differences in heat balance and heat transfer (lower R + C, E_{sw} and $(T_{re} - \bar{T}_{sk})$ for the women) are not altered by the acclimation process.

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Table 1. Physical characteristics of the subjects.

	Males			Females		
Number of subjects		10			9	
Age (yr)	21.1	$\pm$	0.6	22.0	$\pm$	1.0
Height (cm)	178.6	$\pm$	2.1	161.5	$\pm$	2.3
Weight (kg)	75.6	$\pm$	4.2	56.6	$\pm$	2.6
Body fat (%)	17.7	$\pm$	1.6	29.6	$\pm$	1.5
Skin surface area (m^2)	1.93	$\pm$	0.06	1.59	$\pm$	0.04
$\dot{V}O_2$ max ($mmol \cdot kg^{-1} \cdot min^{-1}$)	2.33	$\pm$	0.10	1.81	$\pm$	0.07
$\dot{V}O_2$max ($ml \cdot kg^{-1} \cdot min^{-1}$)	52.3	$\pm$	2.2	40.5	$\pm$	1.5

Values are mean $\pm$ SE.

(The results in brackets from the last line of the table are in the traditional units of $ml \cdot kg^{-1} \cdot min^{-1}$).

Table 2. Differences in thermoregulation between males (M) and females (F) during the 1st day (1st) and 6th day (6th) of heat acclimation.

	1st day		6th day		P	P
	M	F	M	F	M vs F	1st vs 6th
Final T_{re}, °C	38.40 ± 0.09	38.89 ± 0.12	37.94 ± 0.08	38.19 ± 0.07	0.005	0.001
Final HR, b·min^{-1}	147.0 ± 15.0	157.3 ± 9.1	117.0 ± 10.8	130.1 ± 4.6	N·S	0.001
$\bar{T}_{sk}$, °C	36.30 ± 0.15	36.99 ± 0.22	35.93 ± 0.14	36.44 ± 0.14	0.01	0.005
$\dot{m}_{sw}$, g·m^{-2}·h^{-1}	446.5 ± 15.0	447.7 ± 17.5	470.7 ± 18.6	436.1 ± 14.9	N·S	N·S
M, W·kg^{-1}	5.21 ± 0.10	5.03 ± 0.10	5.00 ± 0.14	5.00 ± 0.10	N·S	N·S
ΔS, W·kg^{-1}	0.62 ± 0.08	0.94 ± 0.10	0.56 ± 0.06	0.57 ± 0.06	N·S	0.01
R + C, W·m^{-2}	132.2 ± 2.2	121.0 ± 1.3	127.6 ± 3.0	122.8 ± 2.2	0.001	N·S
E_{sw}, W·m^{-2}	277.7 ± 3.5	237.3 ± 4.4	276.8 ± 6.4	254.4 ± 6.4	0.001	N·S
Δ($T_{re}-\bar{T}_{sk}$), °C	1.54 ± 0.17	0.97 ± 2.22	1.74 ± 0.18	1.31 ± 0.19	0.05	N·S
h_k, W·m^{-2}·°C^{-1}	115.8 ± 17.3	116.4 ± 10.9	107.1 ± 10.5	105.2 ± 11.8	N·S	N·S

Values are means ± SE.

FIGURE LEGENDS

Figure 1.   Sweat rate during six days of heat acclimation for the males (solid line) and the females (dashed line), presented in $g \cdot kg^{-1} \cdot h^{-1}$ and $g \cdot m^{-2} \cdot h^{-1}$.

Figure 2.   Final heart rate ($b \cdot min^{-1}$) during the six days of acclimation for the males (solid line) and the females (dashed line).

Figure 3.   Final rectal temperature (^{o}C) during the six days of acclimation for the males (solid line) and the females (dashed line).
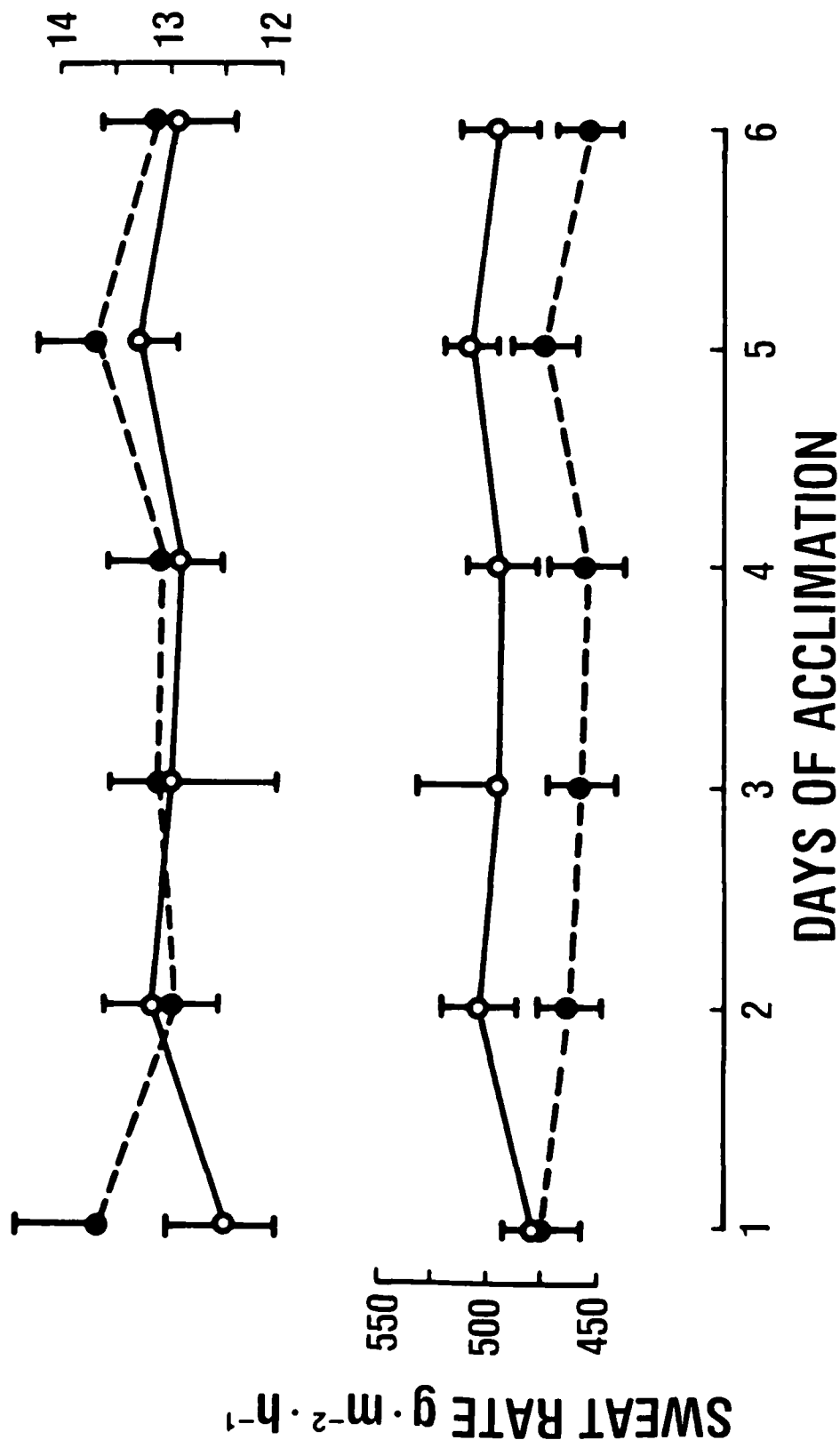
Figure 1 – Heat Acclimation of Men and Women
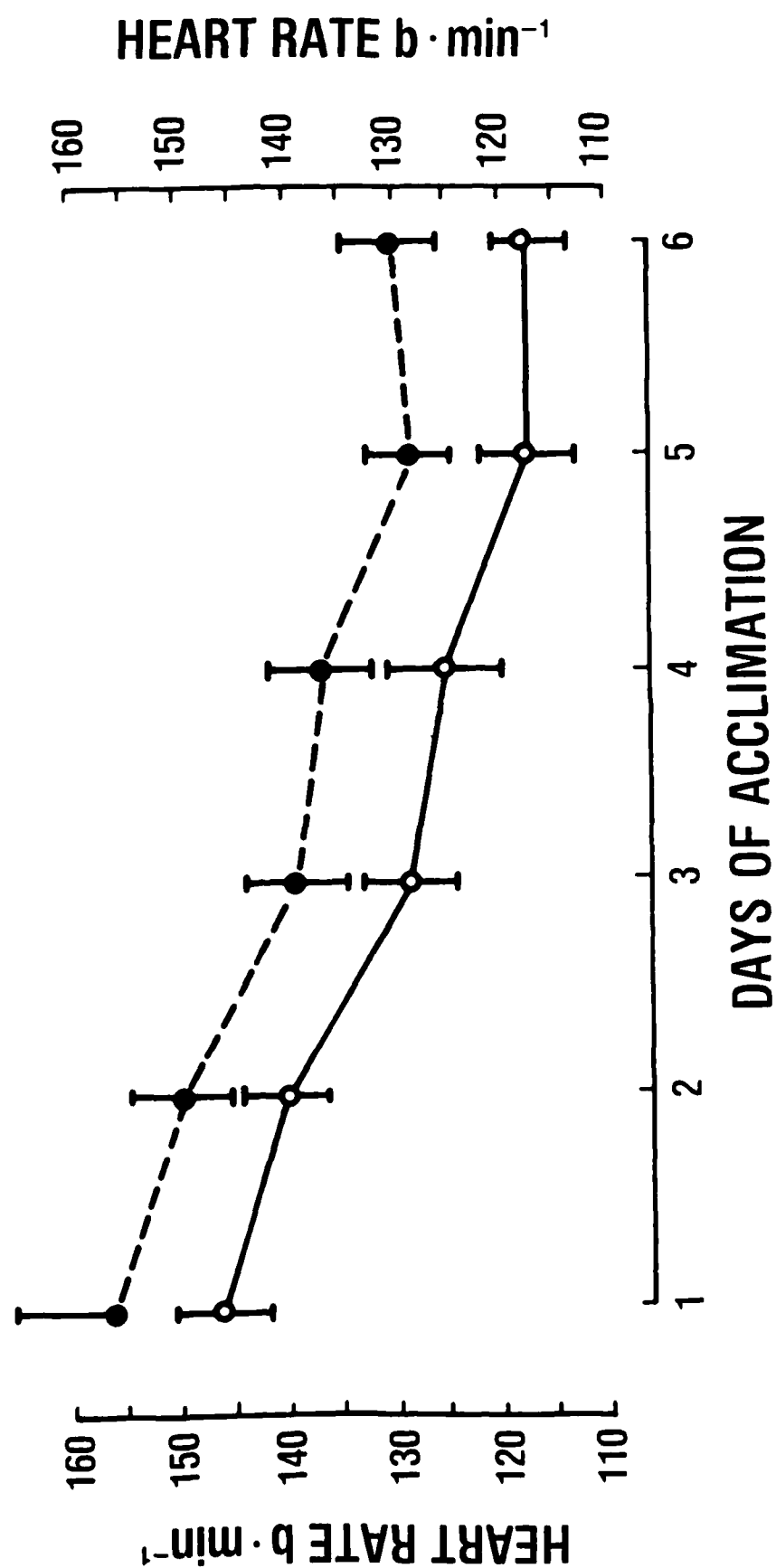
Figure 2 - Heat Acclimation of Men and Women
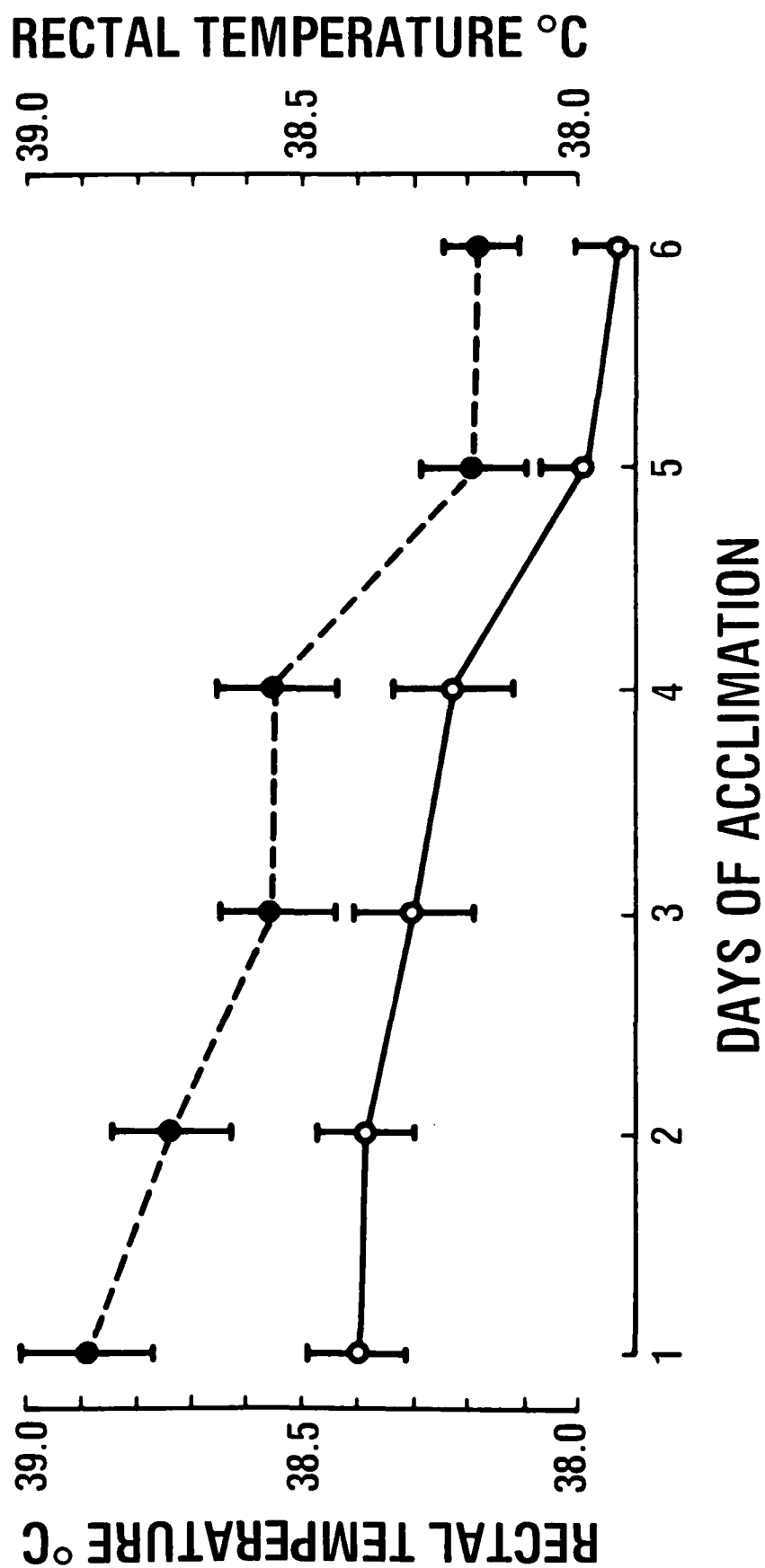
Figure 3 - Heat Acclimation of
Men and Women

PHYSIOLOGICAL RESPONSES OF MEN AND WOMEN TO HUMID AND DRY HEAT

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ABSTRACT

Sex-related differences were evaluated in 10 males and 9 females under hot-wet and hot-dry conditions. Preacclimatized subjects were exposed to a comfortable climate (20°C, 40% rh), mild-wet weather (32°C, 80% rh), two hot-wet conditions (35°C, 90% rh; 37°C, 80% rh) and two hot-dry conditions (49°C, 20% rh; 54°C, 10% rh). Exposures lasted 120 min: 10' rest, 50' walk (1.34 m$\cdot$s^{-1}), 10' rest, 50' walk. During hot-dry exposures, heart rate (HR) and rectal temperature (T_{re}) were significantly lower for males than females by 13 and 20 beats$\cdot$min^{-1} and by 0.25 and 0.32°C for the two conditions; no significant differences in sweat loss ($\dot{m}_{sw}$) were observed. During hot-wet exposures, both mean final T_{re} and $\dot{m}_{sw}$ were lower in females than males by 0.34 and 0.24°C and by 106 and 159 g$\cdot$m$^{-2}\cdot$h^{-1}, respectively (males sweated 25 and 40% more than females). None of these differences correlated with maximal oxygen uptake, body weight, skin surface area or percentage of body fat. During hot-wet exposures, a negative relationship between surface area-to-mass ratio (A_D/wt) and T_{re}, mean skin temperature, HR and change in heat storage was found. It was suggested that three major factors are involved in these differences: (a) higher A_D/wt for females than for males, (b) better sweat suppression from skin wettedness for women, and (c) higher thermoregulatory set point for women than for men.

Index terms: sex-related differences; humid and dry heat; rectal temperature; heart rate; mean skin temperature; sweat loss; maximal oxygen uptake; body weight; skin surface area; body fat percentage; surface area-to-mass ratio; sweat suppression; thermoregulatory set point

INTRODUCTION

The reactions of men to changes in environmental temperature have served as the basis for our understanding of human heat tolerance and thermoregulation. There appears to be less certainty about the thermoregulatory patterns of women, however. Physiological responses to heat stress may be expected to differ in men and women due to several possible factors, including the lower cardiorespiratory fitness (7,9,20,23), the higher body fat content (1,31), the lower body weight (28), the lower skin surface area and the higher surface area-to-mass ratio (A_D/wt) (12,25) of women compared to men. In addition, the fluctuating hormonal levels of estrogen and progesterone accompanying the menstrual cycle may also influence women's tolerance to heat stress (2,15,19).

Several studies have shown that women thermoregulate less effectively than men when exposed to an acute heat stress (3,6,27,32). Under the same heat load, core temperatures and heart rates were higher (3,13,16,27,32) and sweat rates were substantially lower (10,13,16,32) in women. However, when the cardiorespiratory fitness of the men and women was considered, physically fit women were found to have similar (8,18) or even lower (23,30) core temperatures and heart rates than fit men during an acute heat exposure despite their lower rates of sweating. Although heat acclimatization served to eliminate many of the sex-related physiological differences, sweat rates still remained lower for women (30,32).

One of the sources for the controversy in the literature regarding apparent sex-related thermoregulatory differences may result from the environmental conditions under which the experiment was conducted. Although little research has been performed comparing the responses of a group of men and women to both dry and humid climates, it appears that women may have a physiological advantage when

tested under humid heat (21,30). In environments in which high rates of cooling by evaporation are not possible, the higher A_D/wt of women would allow both for more surface area for evaporative heat loss in relation to the heat produced by metabolism and for more heat loss via radiation and convection. The latter, however, is only true in environments in which ambient temperature is lower than skin temperature. In addition, the lower sweat rate of women should also prove advantageous under conditions in which the evaporative capacity of the environment is a limiting factor to evaporative cooling since less body fluids would be lost as sweat. Under dry conditions, when sweat output becomes increasingly important, the higher sweat rate of men may put them at an advantage over women.

If thermoregulatory function of the sexes is altered by climatic differences, the sex-related differences will have to be defined and explained separately for different climatic conditions. The purpose of this study, therefore, is to define the possible physiological differences between the sexes for humid and dry heat and to suggest the thermoregulatory mechanisms involved.

METHODS

Nine female and 10 male volunteer soldiers served as subjects. All subjects were totally informed with regard to experimental risk and gave their written informed consent. The physical characteristics of the females (mean $\pm$ SE) were: age, 22.0 ± 1.0 yr; height, 161.5 ± 2.3 cm; weight, 56.6 ± 2.6 kg; body fat, $29.6 \pm 1.5\%$ as determined by the method of Durnin and Womersley (11); body surface area, 1.59 ± 0.04 m^2; A_D/wt, 283.0 ± 5.7 cm$^2 \cdot$kg^{-1}; and maximal oxygen uptake ($\dot{V}O_2$ max), 40.5 ± 1.5 ml$\cdot$kg$^{-1}\cdot$min^{-1} (range $= 34.2$ to 48.3) while the males were: age, 21.1 ± 0.6 yr; height, 178.6 ± 2.1 cm; weight, 75.6 ± 4.2 kg; body fat, $17.7 \pm 1.6\%$; body surface

area, 1.93 ± 0.06 m^2; A_D/wt, 258.9 ± 6.5 cm$^2 \cdot$kg^{-1}; and $\dot{V}O_2$ max, 52.3 ± 2.2 ml$\cdot$kg$^{-1} \cdot$ min^{-1} (range = 44.7 to 62.4). All experiments were conducted during early spring months.

Prior to the heat exposures, all subjects underwent medical examination, anthropometric measurements (height, weight, skinfold thickness) and determination of $\dot{V}O_2$ max. Maximal oxygen uptake was determined from an intermittent treadmill running test utilizing methods and techniques modified from Taylor et al. (29). During these tests, expired air was collected in Douglas bags; the volume was measured in a Collins Spirometer and converted to standard environmental conditions (STPD); and the O_2 and CO_2 concentrations were measured with an Applied Electrochemistry Model S-3A O_2 analyzer and Beckman LB-2 infrared CO_2 analyzer. Heart rate was calculated from R-R (ECG) intervals recorded on a Hewlett-Packard Model 1511A Electrocardiograph.

The nineteen male and female subjects, dressed in T-shirts, shorts, socks and indoor shoes, were then concurrently acclimatized for 6 consecutive days by walking on a level motor-driven treadmill at 1.34 m$\cdot$s^{-1} for two 50-min periods with a preceding and intervening 10-min rest period, at 49°C, 20% rh, 1 m$\cdot$s^{-1} wind speed. After this acclimatization period, the subjects were exposed to six environmental variations: a comfortable (control) climate (T_a = 20°C, rh = 40%, P_a = 7.0 Torr, WBGT = 14.4°C), a mild-wet climate (T_a = 32°C, rh = 80%, P_a = 28.5 Torr, WBGT = 30.3°C), two hot-wet climates (T_a = 35°C, rh = 90%, P_a = 37.9 Torr, WBGT = 34.0°C; T_a = 37°C, rh = 80%, P_a = 37.7 Torr, WBGT = 34.5°C) and two hot-dry climates (T_a = 49°C, rh = 20%, P_a = 17.6 Torr, WBGT = 34.0°C; T_a = 54°C, rh = 10%, P_a = 11.3 Torr, WBGT = 34.2°C). Wind speed for all six climates was constant at 1 m$\cdot$s^{-1}. The WBGT was similar for the two hot-wet compared to the two hot-dry environments. Each of these six exposures lasted 120 min: 10' rest, 50' walk, 10'

rest, 50' walk. Subjects walked at the same speed (1.34 m·s^{-1}) on a level treadmill during these exposures as during acclimatization and were similarly dressed.

During all heat exposures, rectal temperature (T_{re}) was recorded from a Y.S.I. rectal thermistor probe inserted ~ 10 cm beyond the anal sphincter. Skin temperatures were monitored with a three-point thermocouple skin harness (chest, calf and forearm) and mean weighted skin temperature ($\bar{T}_{sk}$) was calculated according to Burton (5). Using a Hewlett Packard 9825A Calculator and 9862A Plotter on-line during experimentation, both $\bar{T}_{sk}$ and T_{re} were plotted for each subject at approximately 2-min intervals. Heat storage (ΔS) was calculated as follows: $\Delta S = 0.965 \, (0.8 \, \Delta \, T_{re} + 0.2 \, \Delta \, \bar{T}_{sk})$ in W·kg^{-1}. Heart rate was measured by radial artery palpation during the rest periods and after each 25 min of walking. Ad lib drinking was encouraged. Total body weight losses were determined from pre- and post-walk measurements on a K-120 Sauter precision electronic balance (accuracy of $\pm$ 10 g) for calculation of sweat rate. Sweat rate ($\dot{m}_{sw}$) was determined by loss of weight adjusted for water intake and urine output. Respiratory and metabolic weight losses were considered negligible and were not taken into account (17). At the end of the first rest period and at the end of each walking period, two-minute expired air samples were collected in Douglas bags and analyzed as previously described for calculation of metabolic rate. Criteria for terminating any heat exposure were a HR of 180 beats·min^{-1} during exercise or of 140 beats·min^{-1} during rest and/or a T_{re} above 39.5°C, dizziness, nausea, or dry skin.

Statistical Treatment

Most variables were evaluated by use of a mixed design of two factors, with one factor being the two groups (male and female) and the other being the treatment (environmental conditions) which both groups received. When the subjects were separated by "degree of fitness" or other subgroup contrasts, a one-

way analysis of variance was used to search for significant differences. In either design, if a significant F-value was found ($P < 0.05$), critical differences were analyzed by Tukey's procedure to locate the significant mean differences.

RESULTS

During heat acclimatization, mean final HR dropped 27 beats·min^{-1} in females and 30 beats·min^{-1} in males, final T_{re} dropped 0.46 and 0.70°C for males and females, respectively, and $\dot{m}_{sw}$ remained unchanged in both sexes. Although females maintained higher HR and T_{re} than males, both sexes showed similar trends in these parameters during acclimatization. More importantly, non-significant differences in physiological responses (HR and T_{re}) for both sexes during the last two acclimatization days (days 5 and 6) indicated a physiological acclimatization to the dry heat.

Figure 1 illustrates the mean changes in final T_{re} for males and females during the comfortable, mild-wet, hot-wet and hot-dry environments. No significant difference ($P > 0.05$) between the sexes was found for final T_{re} during the comfortable conditions (20°C, 40% rh). However, the T_{re} of males were higher than those of females for all wet conditions. This difference varied from 0.15°C in the mild-wet to 0.34°C in the 90% rh condition with the latter being statistically significant ($P < 0.05$). In contrast, under the hot-dry conditions, the final T_{re} of males was 0.25 and 0.32°C lower than females for the 49°C, 20% rh and 54°C, 10% rh environments, respectively. The difference between the sexes at 54°C, 10% rh was statistically significant ($P < 0.05$). When the environmental conditions were compared according to equal WBGT, the females were found to have the same final T_{re} value for 35°C, 90% rh and 49°C, 20% rh (WBGT $\simeq$ 34°C) as well as for the 37°C, 80% rh and 54°C, 10% rh conditions (WBGT $\simeq$ 34.5°C). The males, however,

displayed significantly higher final T_{re} values for the wet conditions of these corresponding climatic (WBGT) contrasts.

As seen in Table 1, the final mean observations of $\bar{T}_{sk}$ for the men and women for the various climatic conditions were similar in trend to the corresponding T_{re} responses. The $\bar{T}_{sk}$ for the females was higher in the hot-dry conditions but lower than the males in the hot-wet conditions. The differences between the sexes were statistically significant for the $32^{o}C$, 80% rh and $54^{o}C$, 10% rh climates with a full degree centigrade difference between the sexes for the latter condition (see Table 1).

The analysis of group heat storage comparisons utilized the difference between the initial and final heat storage values (Δ heat storage in $Watt{\cdot}kg^{-1}$) each hour. Obviously, the change in heat storage (ΔS) reflected alterations in $\bar{T}_{sk}$ and T_{re} with time. Since females exhibited smaller changes in T_{re} and $\bar{T}_{sk}$ than males during the hot-wet conditions, they subsequently demonstrated less change in S during the first hour as seen in Figure 2. Similarly, the larger increases in T_{re} and $\bar{T}_{sk}$ for the females in the hot-dry climates were reflected in their larger ΔS values for the first hour of exposure. The only significant differences between the men and women, however, were for the $35^{o}C$, 90% rh and $54^{o}C$, 10% rh environments ($P < 0.06$, see Table 1). During the second hour, under the dry conditions, the ΔS were negligible (0.015 and 0.099 $W{\cdot}kg^{-1}$ for the males and 0.078 and 0.089 $W{\cdot}kg^{-1}$ for the females). Under the hot-wet environments, the second hour ΔS were 30-50% of the corresponding first hour values.

As expected, no sex-related differences were found for metabolic rate in either the dry or wet conditions. These climatic contrast values are presented in Table 1.

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The sex-related differences for final mean HR responses for the various climatic conditions are presented in Figure 3. Similar HR responses were observed for both sexes during the control condition and during the hot-wet conditions. Although the responses of the males were slightly higher for the wet conditions, these differences were not significant. In the dry heat, however, there was a significant difference ($P < 0.05$) in the HR response, with the males averaging 13 and 20 beats$\cdot$min^{-1} lower than the females (see Table 1).

Sweat rate responses for the various environmental conditions are presented in Figure 4. Similar $\dot{m}_{sw}$ (g$\cdot$m$^{-2}\cdot$h^{-1}) were observed in the control condition for both sexes. In the hot-wet conditions males were found to sweat more than females. In the most severe humid climate (37°C, 80% rh), males sweated 40% more than females (560 and 401 g$\cdot$m$^{-2}\cdot$h^{-1}, respectively), with the difference being highly significant ($P < 0.01$). In the other two wet conditions (32°C, 80% rh and 35°C, 90% rh), males had a 23% greater sweat output than females over the 2-hour exposure. This difference was only significant ($P < 0.01$) for the latter condition, however (see Table 1). Although males demonstrated a higher sweat rate than females in the dry conditions, these differences were not statistically significant (see Table 1). When the sweat loss was expressed in g$\cdot$kg$^{-1}\cdot$h^{-1} rather than in g$\cdot$m$^{-2}\cdot$h^{-1}, the same sex-related observations were seen for the control condition and wet climates, as seen in Table 1. In the dry climates, however, the females were seen to sweat more per unit weight than the males but not significantly so.

No significant differences in water consumption or state of hydration were found between sexes in the control or the mild-wet conditions (Table 1). In the other four conditions (hot-wet and hot-dry), the females drank proportionately more than the males (10-37% more when calculated as a percentage of lean body mass). However, these were not statistically significant differences. Although no statisti

cally significant differences in the sex-related state of hydration were observed for these climatic conditions, the females were found to be less dehydrated than the males in the hot-wet climates (30-47% less) as shown in Table 1.

Each sex was divided into two subgroups (a high group and a low group) according to the following five parameters: $\dot{V}O_2$ max, body weight, surface area, percentage of body fat, and surface area-to-mass ratio (A_D/wt). Each subgroup was arranged in such a manner so that comparisons could be made of similar male and female subgroups for each parameter. For example, the five less physically fit males had similar $\dot{V}O_2$ max compared to the five more fit females (P > 0.05).

When the thermoregulatory responses of the subjects in various climates were correlated with each of these five parameters, no significant relationships were found with physical fitness (Table 2), body weight, surface area, or percentage body fat. There was, however, some correlation between physiological responses and A_D/wt. When the male and female subgroups were matched for A_D/wt no differences were found for final T_{re}, $\bar{T}_{sk}$, ΔS and HR in the hot-wet climates, as seen in Table 3. The $\dot{m}_{sw}$, however, was still higher for the males than for the females (11.19 $g \cdot kg^{-1} \cdot h^{-1}$ for females and 14.61 for males). In the hot-dry conditions, these same subgroups differed from each other in the thermoregulatory responses, i.e., the women's T_{re} and HR were significantly higher for both days while $\bar{T}_{sk}$ and ΔS were significantly higher only at $54^{\circ}C$. No further correlation was found for thermoregulatory responses between the different phases of the menstrual cycle or between the natural cycle and the artificial one (contraceptive), either in humid or dry environments.

DISCUSSION

The major objective of this study was to determine whether sex-related differences in thermoregulation exist; and if so, whether there was any method to define these differences. A major methodological problem of the study was the inability to find groups of males and females matched in all their physical characteristics, namely: body weight, skin surface area, percentage of body fat and cardiorespiratory physical fitness. This problem was partially solved by dividing each sex into two subgroups and matching the subgroups as "small" males vs. "big" females, or more fit females vs. less fit males.

The sex-related differences concluded from this investigation are summarized in Table 4. In comfortable climatic conditions ($20^{\circ}C$, 40% rh) men and women reacted in a physiologically similar fashion. Under wet conditions, whether mild or hot, females tolerated the heat better than males. They displayed lower deep body and skin temperatures, and therefore *lower heat storage*, while demonstrating lower sweat rates and subsequently less dehydration than males. In contrast, under hot-dry conditions, males seemed to be at a physiological advantage. Compared to females, they showed lower deep body and skin temperatures, lower HR, lower ΔS, and similar sweat rates. These differences in temperatures and ΔS were significant only at $54^{\circ}C$.

Thus, there appear to be sex-related differences in thermoregulation but the physiological advantage seems to be related to the type of climate, particularly whether the environment is wet or dry. Sex-related differences in thermoregulation suggest to some the importance of the sex hormones as a primary mechanism. We suggest from the present findings that the sex hormone influence in thermoregulation can be excluded as a critical factor for several reasons. First, in explaining

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male-female differences in thermoregulation the hormonal level should not react preferentially to hot-dry or hot-wet climates, but should show a similar response to increased environmental heat, which it did not in this study. Secondly, no effect of the menstrual phase appeared evident in our group of females when they were divided into two subgroups: those exposed to the different climatic conditions before, and those exposed, after ovulation. In addition, the women who were taking oral contraceptive (n=4) showed the same responses to the changing environments as the other women. This lack of effect of menstrual stage on heat tolerance is in agreement with the findings of others (12,15,17,26).

Differences in the physical characteristics of men and women are also thought to be important factors to be considered in making comparisons between the sexes. As expected, the women in this study were shorter, lighter, fatter and less physically fit than the men. Thus, each of these factors could be thought of as a possible cause in sex-related thermoregulatory differences. However, analysis according to matched subgroups yielded no relationship between the climatic differences observed and the physical characteristics of the sexes. Thus, women cannot be defined as "smaller, fatter, less fit men" for thermoregulatory purposes.

Only one anthropometric factor, the surface area-to-mass ratio (A_D/wt), was found to be related to the specific physiological adjustments to the various climates (wet and dry). As expected (22), this ratio was 10% higher for the females than for the males. Matching the five women with the lower A_D/wt to the five men with the higher A_D/wt (Table 3) yielded two subgroups with similar A_D/wt. Further comparison of these two subgroups showed a similarity in mean final T_{re}, $\bar{T}_{sk}$, ΔS and HR during exposure to hot-wet conditions, but the males sweated 30% more. These observations can be explained in part by two different mechanisms. First, a higher A_D/wt is an advantage in humid climates. Heat production is mainly weight-

dependent, while heat dissipation is related to the skin surface area. In hot-wet environments, one cannot evaporate necessary requirements; therefore, the more surface area available in relation to the heat produced, the greater the cooling power (25). Secondly, since a high sweat rate would be ineffectual in climates that do not allow for adequate evaporation, the body can conserve its water by suppression of the non-evaporative sweat loss. The women, who demonstrated lower sweat rates during exposure to the wet climates, were therefore at an advantage since they became less dehydrated than the men while working in the heat (Table 1). Although the reason for the often documented lower sweat rates of women in humid conditions is not clearly defined, it may be attributable to the more rapid development of hidromeiosis (4,30), or suppression of sweating, which is related to skin wettedness (4). Females may have a better and more efficient feedback from skin wettedness than males which thus suppresses the nonevaporative sweat loss in humid heat.

In hot-dry environments, the former mechanisms do not function in the same fashion. The sweat suppression mechanism is irrelevant in hot-dry climates because the skin is almost dry. In dry environments, higher sweat production results in higher cooling power. In these conditions when nearly all sweat evaporates, both sexes needed similar evaporative cooling to dissipate a comparable metabolic load. This can explain the similarity in sweat loss for both sexes in dry climates. In dry conditions, a high A_D/wt can be a disadvantage because it allows rapid forced heat gain by convection and radiation (12,25). In this case, a high A_D/wt works in two different directions and results in more evaporative cooling power on the one hand, and more heat gain from the environment on the other hand. Within the sexes a small advantage, if any, was found in having a higher A_D/wt in dry climates, but not of the magnitude as in humid environments. No similarity between subgroups of the

sexes was found in the dry climatic exposures; thus the importance of A_D/wt in dry climates is very small.

We suggest that the differences in the dry environments can be explained in large part by different thermoregulatory set points for the sexes; higher for the women than for the men. This hypothesis can be supported by the evidence that during the second hour of the dry-climatic exposures both sexes were under thermal equilibrium, with negligible heat storage. The higher thermoequilibrium of the females is most probably the result of a higher thermoregulatory set point. Sweating would thus be initiated at a higher core temperature (2,13) and more heat storage would occur as was the case in the $54^\circ C$, 10% rh environment (Table 1). In support of this contention, Roberts et al. (24) showed sweating onset in terms of lower esophageal temperature to be reduced for males as compared to females ($0.2^\circ C$ difference pre-training, pre-acclimation; $0.3^\circ C$ post-training; and $0.4^\circ C$ post-acclimation). In hot-wet conditions both sexes did not reach thermoequilibrium (2nd hour ΔS were 30-50% of the corresponding 1st hour values), therefore the final T_{re} cannot be an indicator of the thermoregulatory set point. This helps explain the female's lower final T_{re} in spite of a higher thermoregulatory set point. One possible reason for not reaching thermoequilibrium in these conditions might be a lack of full acclimatization to hot-wet climates since it is known that acclimatization to dry heat does not provide sufficient acclimatization to wet heat (14).

It can be concluded that females and males react in a physiologically similar manner under comfortable environmental conditions, females tolerate hot-wet climates better than males, and males better tolerate hot-dry conditions. A possible explanation for these differences involves three considerations. The higher A_D/wt for females may be a morphological advantage in hot-wet climates, and a disadvantage in hot-dry environments. Females seem to have better peripheral feedback

from skin wettedness, which suppresses nonefficient sweating in humid conditions. Females also appear to have a higher central thermoregulatory set point than males, and therefore are more intolerant of hot-dry environments as compared to males.

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TABLE 1. Sex differences in the various climatic conditions (mean and S E) for males (M) and females (F)

T_a °C, rh %	CONTROL 20°C, 40%		MILD-WET 32°, 80%		HOT-WET 35°, 90%		HOT-WET 37°, 80%		HOT-DRY 49°, 20%		HOT-DRY 54°, 10%	
	M	F	M	F	M	F	M	F	M	F	M	F
Final T_{re} °C	37.53 .07	37.60 .08	37.82 .08	37.67 .04	38.52 .11	38.18* .07	38.73 .09	38.49 .07	37.94 .08	38.19 .07	38.12 .09	38.44* .10
Final HR beats·min^{-1}	85.9 2.6	85.2 3.0	105.1 2.4	102.4 2.7	138.7 4.7	136.8 3.2	148.8 3.8	143.0 3.0	117.0 3.4	130.1* 4.6	127.3 5.1	147.9* 1.6
Final $\bar{T}_{sk}$ °C	31.02 .33	30.49 .40	34.13 .15	33.43* .13	36.17 .09	35.77 .10	36.51 .08	36.30 .11	35.80 .20	36.23 .29	36.29 .17	37.30* .14
Metabolism ml·kg^{-1}·min^{-1}	14.34 .46	13.93 .29	14.66 .40	13.85 .37	15.25 .53	14.74 .28	14.74 .62	14.38 .33	14.42 .39	14.35 .31	14.64 .38	14.39 .34
ΔS – 1st hour watt·kg^{-1}	.112 .074	.055 .051	.381 .064	.219 .042	.978 .067	.697** .081	.949 .070	.751 .048	.560 .055	.569 .062	.619 .060	.900** .097
$\dot{M}_{sw}$ g·kg^{-1}·h^{-1}	2.34 .26	2.33 .24	7.52 .32	6.70 .31	14.27 1.03	12.65 .63	14.46 .66	11.32* .88	12.98 .58	13.08 .50	15.11 .54	16.49 .77
$\dot{M}_{sw}$ g·m^{-2}·h^{-1}	92 12	84 10	293 16	238 14	554 41	448* 22	560 26	401* 30	502 19	462 15	586 23	582 24
Dehydration % of LBM	.225 .079	.222 .094	.550 .160	.632 .218	1.412 .207	.990 .229	1.136 .202	.607 .282	1.303 .148	1.197 .200	1.178 .256	1.152 .236
H_2O Consumption % of LBM	.35 .11	.45 .07	1.29 .25	1.29 .25	2.06 .21	2.63 .28	2.38 .21	2.62 .17	1.85 .15	2.53 .25	2.50 .22	3.21 .24

* $p < 0.05$
** $p < 0.06$

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TABLE 2. Cardiovascular physical fitness and thermoregulation

	MALES		FEMALES	
	MORE FIT	LESS FIT	MORE FIT	LESS FIT
No. of Subjects	5	5	5	4
$\dot{V}O_2$ max ml·kg^{-1}·min^{-1}	58.3 ± 1.7*	46.3 ± 0.6	43.7 ± 1.3	36.6 ± 1.1
HOT-DRY 49°C, 20%				
T_{re}, °C	37.92 ± 0.13	37.96 ± 0.12	38.22 ± 0.06	38.16 ± 0.14
$\bar{T}_{sk}$, °C	35.82 ± 0.16	35.78 ± 0.39	36.40 ± 0.36	36.02 ± 0.53
ΔS, W·kg^{-1}(1st h)	0.572 ± 0.063	0.549 ± 0.097	0.623 ± 0.064	0.501 ± 0.115
HR, beats·min^{-1}	113 ± 6.0	121 ± 3.1	125 ± 4.4	137 ± 8.2
$\dot{M}_{sw}$, g·kg^{-1}·h^{-1}	13.33 ± 0.77	12.63 ± 0.92	13.28 ± 0.41	12.83 ± 1.08
HOT-WET 37°C, 80%				
T_{re}, °C	38.69 ± 0.15	38.77 ± 0.11	38.48 ± 0.07	38.50 ± 0.14
$\bar{T}_{sk}$, °C	36.50 ± 0.13	36.52 ± 0.12	36.24 ± 0.11	36.38 ± 0.23
ΔS, W·kg^{-1}(1st h)	0.924 ± 0.124	0.975 ± 0.080	0.709 ± 0.050	0.804 ± 0.090
HR, beats·min^{-1}	144 ± 6.5	154 ± 3.2	140 ± 4.6	146 ± 3.3
$\dot{M}_{sw}$, g·kg^{-1}·h^{-1}	15.41 ± 1.02	13.50 ± 0.66	11.65 ± 0.81	10.92 ± 1.84

*Mean ± S E

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TABLE 3. Surface area-to-mass ratio (A_D/wt) and thermoregulation

	FEMALES		MALES	
A_D/wt	Higher A_D/wt	Lower A_D/wt	Higher A_D/wt	Lower A_D/wt
No. of Subjects	4	6	5	5
A_D/wt (cm²·kg⁻¹)	297 ± 5*	272 ± 5	273 ± 5	244 ± 7
HOT-DRY				
T_{re}, °C	38.10 ± 0.11	38.27 ± 0.08	37.85 ± 0.11	38.02 ± 0.12
$\bar{T}_{sk}$, °C	36.30 ± 0.30	36.18 ± 0.50	35.96 ± 0.09	35.64 ± 0.39
ΔS, W·kg⁻¹(1st h)	0.486 ± 0.076	0.635 ± 0.089	0.589 ± 0.055	0.531 ± 0.100
HR, beats·min⁻¹	131 ± 9.7	130 ± 4.2	116 ± 5.5	118 ± 4.6
$\dot{M}_{sw}$, g·kg⁻¹·h⁻¹	13.83 ± 0.76	12.47 ± 0.57	13.38 ± 0.77	12.59 ± 0.91
49°C, 20%				
HOT-WET				
T_{re}, °C	38.35 ± 0.05	38.60 ± 0.09	38.62 ± 0.13	38.84 ± 0.11
$\bar{T}_{sk}$, °C	36.15 ± 0.17	36.44 ± 0.15	36.40 ± 0.10	36.62 ± 0.11
ΔS, W·kg⁻¹(1st h)	0.686 ± 0.022	0.804 ± 0.081	0.834 ± 0.115	1.065 ± 0.046
HR, beats·min⁻¹	140 ± 4.1	145 ± 4.3	147 ± 7.8	151 ± 1.5
$\dot{M}_{sw}$, g·kg⁻¹·h⁻¹	11.49 ± 1.79	11.19 ± 0.91	14.61 ± 1.04	14.30 ± 0.91
37°C, 80%				

*Mean ± S E

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TABLE 4. Summary of sex-related trends in thermoregulatory responses to various climates

	COMFORT	MILD-WET	HOT-WET	HOT-DRY
T_{re}	=			
HR	=	=	=	
$\bar{T}_{sk}$	=			
ΔS	=			= or
$\dot{M}_{sw}$	=			=
Dehydration	=	=		=
H_2O Consumption	=	=		

= No difference

Females are lower than males

Females are higher than males

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FIGURE LEGENDS

FIG. 1. Comparison of mean final rectal temperature (T_{re}) between males (M) and females (F) in a control-comfortable climate (20°C, 40% rh), humid climates (32°C, 80% rh; 35°C, 90% rh; 37°C, 80% rh) and dry climates (49°C, 20% rh; 54°C, 10% rh).

FIG. 2. Comparison of 1st-hour mean heat storage ($\Delta S - W \cdot kg^{-1}$) between males (M) and females (F) in the comfortable climate, the three humid climates and two dry climates.

FIG. 3. Comparison of mean final heart rate (HR) between males (M) and females (F) in the control-comfortable climate, the three humid climates and the two dry climates.

FIG. 4. Comparison of mean hourly sweat rate ($\dot{m}_{sw} - g \cdot m^{-2} \cdot hr^{-1}$) between males (M) and females (F) in the comfortable climate, the three humid climates and the two dry climates.
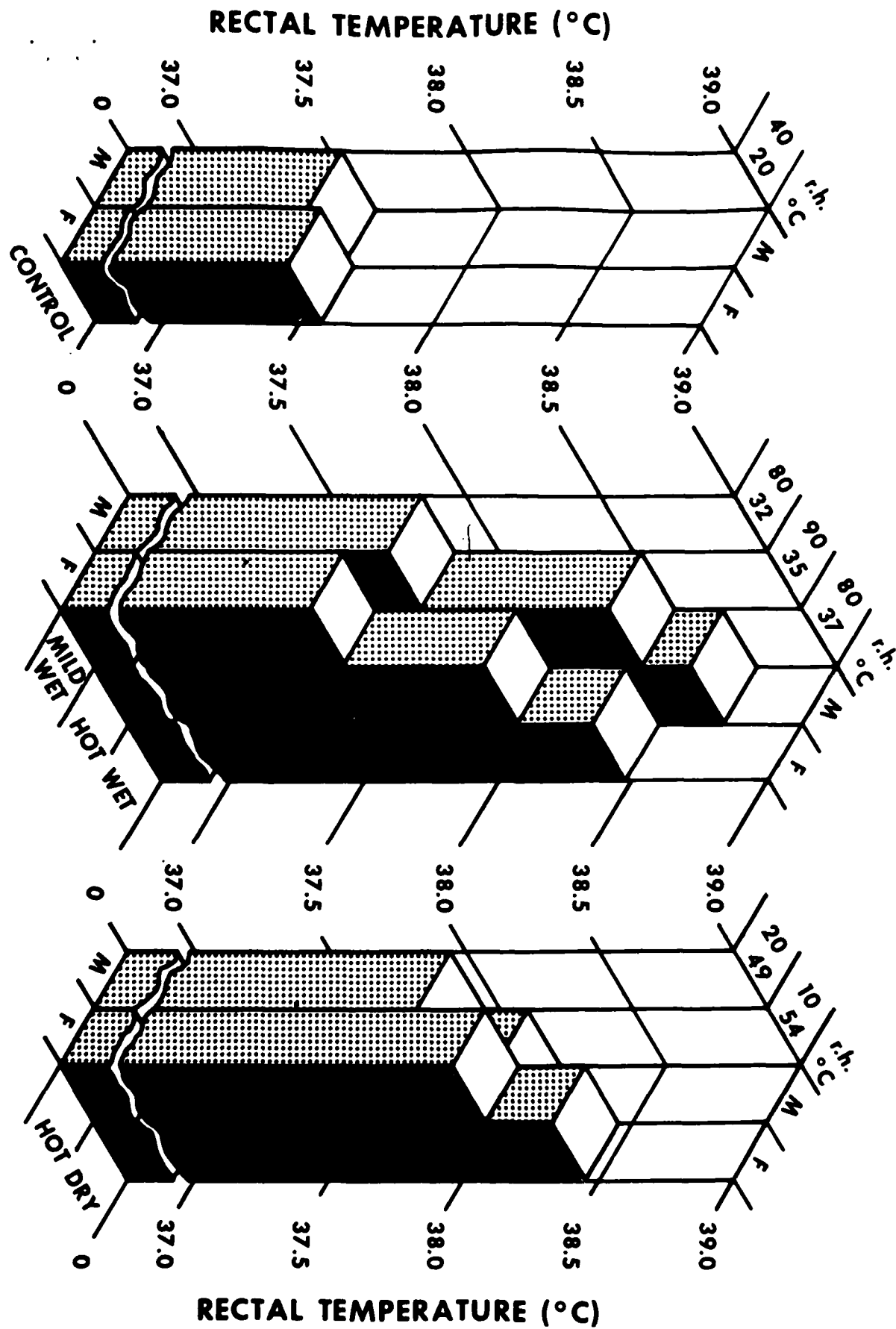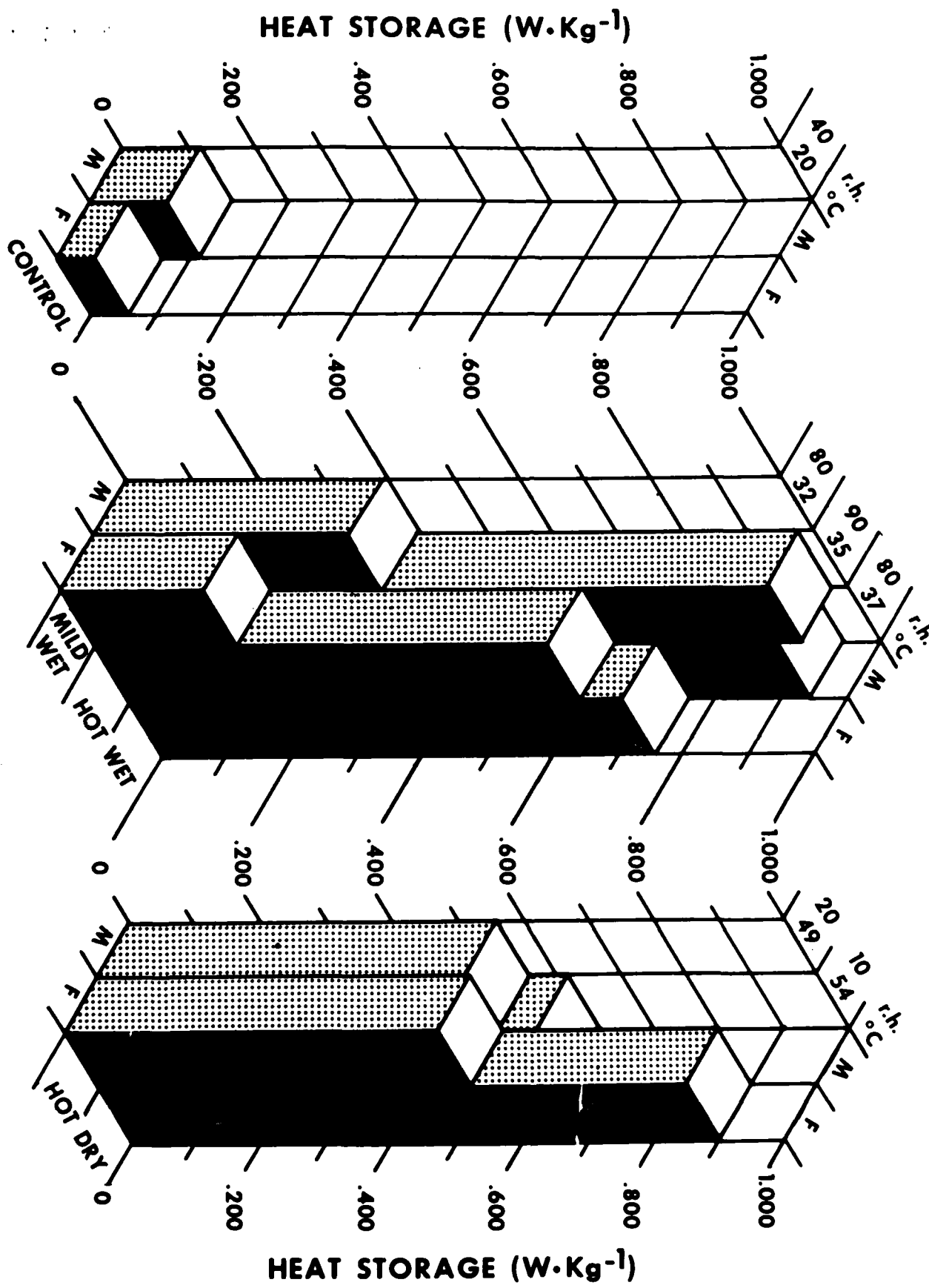
Figure 1 - Heat Reactions of Men and Women

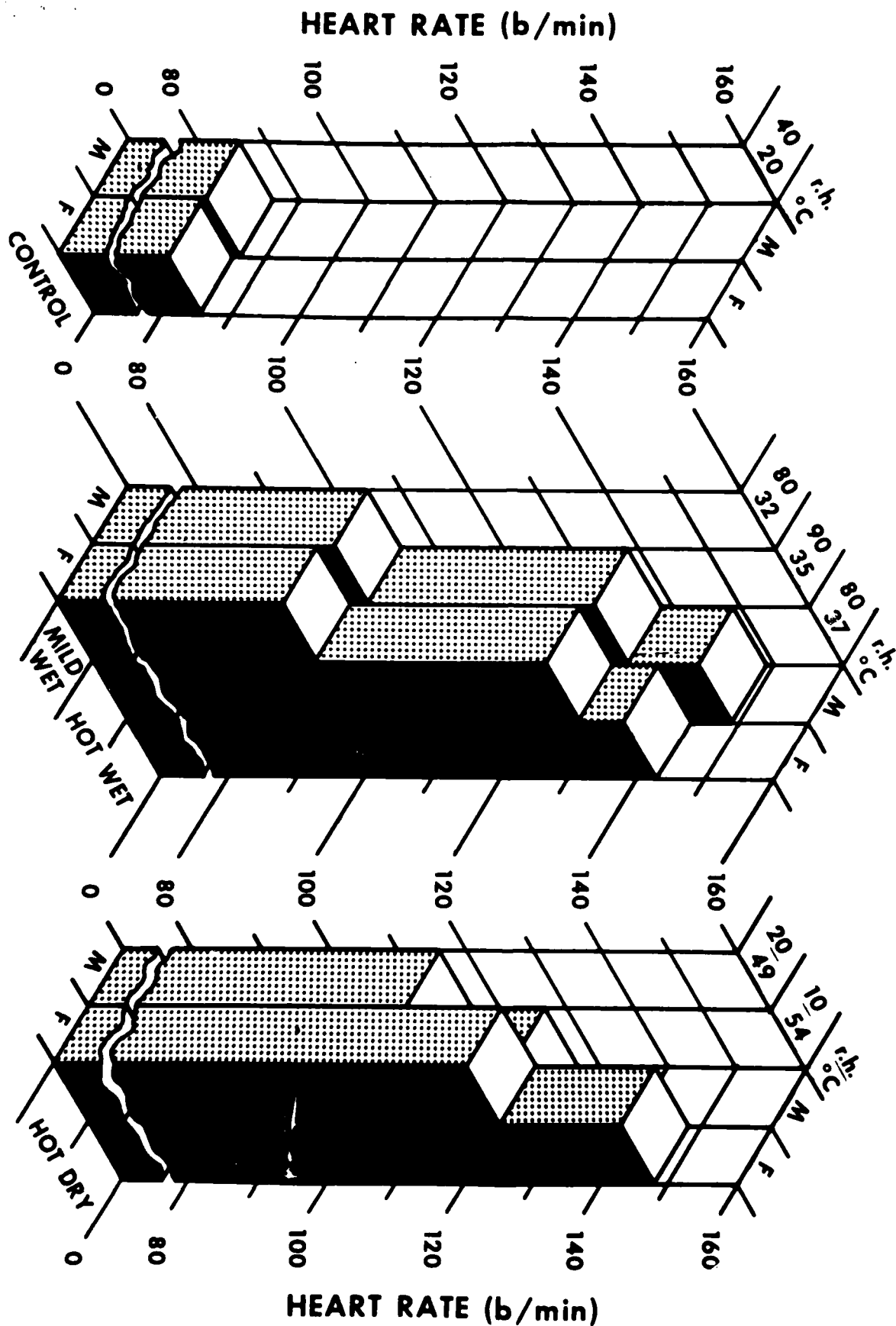Figure 2 – Heat Reactions of Men and Women
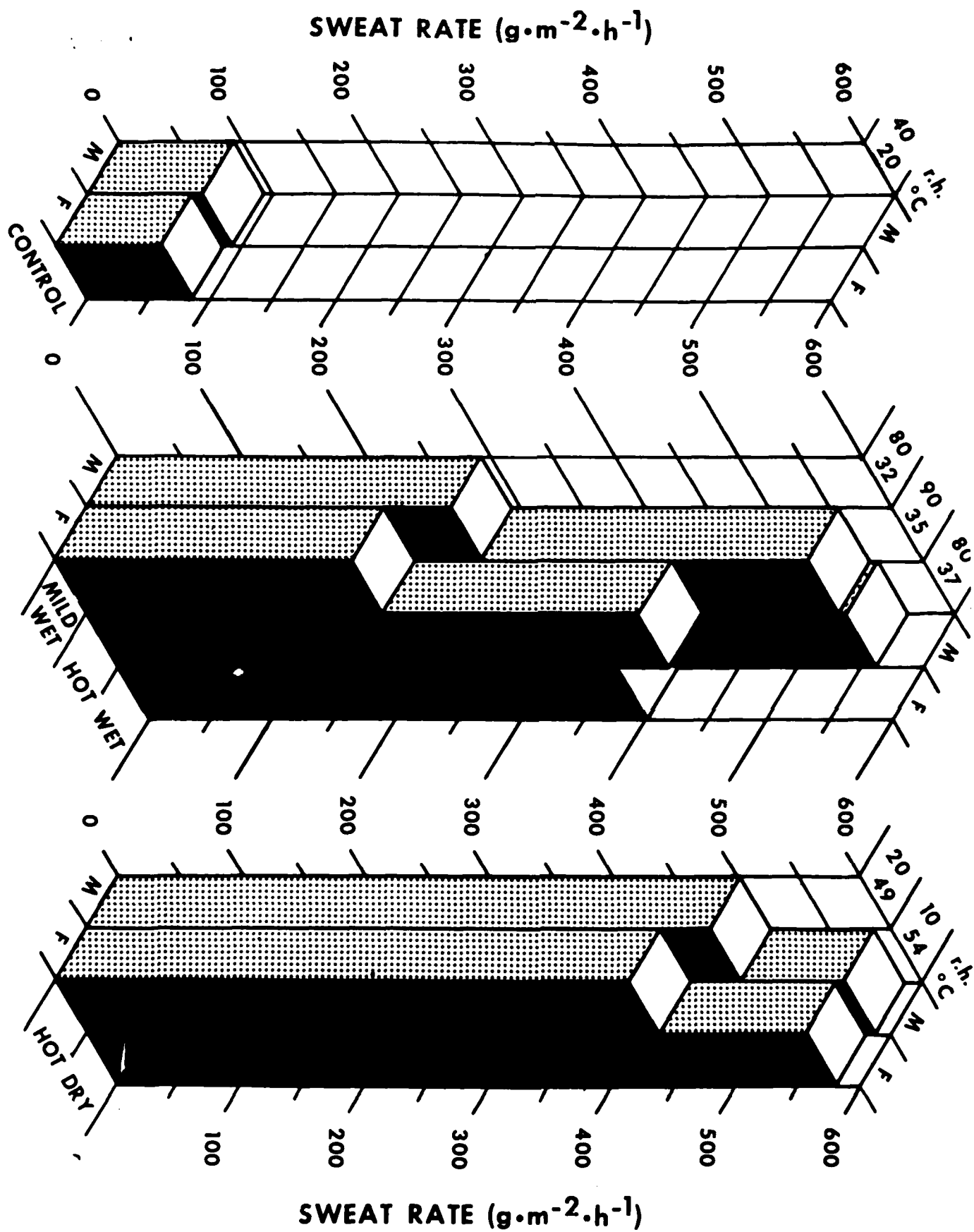
Figure 3 - Heat Reactions of Men and Women

Figure 4 – Heat Reactions of Men and Women

HEAT BALANCE AND TRANSFER IN MEN AND WOMEN

EXERCISING IN HOT-DRY AND HOT-WET CONDITIONS

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Running Head: Heat Balance and Transfer of Men and Women

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ABSTRACT

Sex-related differences in heat balance and transfer were studied in 9 female and 10 male heat-acclimatized subjects exposed to two hot-dry (HD) conditions (49°C, 20% rh; 54°C, 10% rh) and three hot-wet (HW) conditions (32°C, 80% rh; 35°C, 90% rh; 37°C, 80% rh). Exposures lasted 120 min: 10 min rest, 50 min walk, 10 min rest, 50 min walk. Walking speed was $1.34\ \text{m·s}^{-1}$ (level), and for 49°C, 20% rh, in addition, $1.34\ \text{m·s}^{-1}$, 5% grade. No sex-related differences were found in metabolic heat production (M), nor in heat exchange by radiation and convection (R + C) or evaporation (E), when expressed per unit body weight (wt). However, E per unit body surface area (A_D) was lower in females by 9 - 13% ($P < 0.05$ in all HD and 32°C, 80% rh condition) due to their lower M/A_D, and 4-6% lower $(R + C)/A_D$ in HD. Core-to-periphery heat conductance was similar in both sexes despite a lower core-to-skin temperature gradient for women in HD. It was suggested that women have an advantage over men in heat transfer both in HD and HW because of their higher A_D/wt. The disadvantage of a high A_D at high environmental temperatures is diminished by a higher skin temperature, thus reducing (R + C) heat gain. The net effect is to require lower evaporative cooling for women in both HW and HD environments.

INTRODUCTION

Women differ from men in several morphological parameters: their body fat content is higher (1, 19), they have a lower body weight, and they have a higher surface area-to-mass ratio (A_D/wt) (4, 11, 14). Since metabolic heat production during exercise is related to body weight, and heat exchange with the environment is body surface area related, it is expected that the sexes will thermoregulate differently. It is known that females tolerate heat better than males in hot-wet (HW) environments, but worse than males in hot-dry (HD) environments (7, 9, 15, 17). When heart rate (HR) and rectal temperature (T_{re}) were used as indices of heat tolerance, it was shown that in HD conditions both HR and T_{re} were higher for women than for men under the same heat load (2, 5, 7, 15, 16), while lower values were displayed for women under HW conditions (15, 17).

A recent study suggested that women have a higher T_{re} in HD conditions because of a higher thermoregulatory set-point (15); this suggestion is supported by the findings of Roberts et al. (13). However, when the body cannot reach thermoequilibrium as a result of a low evaporative cooling capacity of the environment (E_{max}), the women thermoregulated better than the men as a result of their higher surface area-to-mass ratio (A_D/wt) (15). Some authors have suggested that the high A_D/wt of the female would be a disadvantage when ambient temperature is above skin temperature (4, 11, 14), since the heat gained by radiation and convection (R + C) is a direct positive function of skin surface area, $((R + C) = k \cdot A_D \cdot (T_a - \bar{T}_{sk})$, where T_a = the environmental temperature, $\bar{T}_{sk}$ = mean skin temperature, and k = a constant depending on clothing insulation and air movement around the body). The significance of the higher A_D/wt for women is under controversy in the literature mainly because of a lack of quantitative information.

The purpose of this study is to evaluate heat balance and heat transfer in men and women while exercising under HW and HD conditions, in which air temperature is either above or slightly below skin temperature so that heat can be both lost or gained by R + C. In addition, the importance of differences in surface area-to-mass ratio for the sexes under the above conditions is to be evaluated.

METHODS

Nine female and 10 male volunteer soldiers served as subjects. All subjects were totally informed with regard to experimental risk and gave their written informed consent. The physical characteristics of the females (mean $\pm$ SE) were: age, 22.0 ± 1.0 yr; height, 161.5 ± 2.3 cm; weight, 56.5 ± 2.6 kg; body surface area, 1.59 ± 0.04 m^2; and A_D/wt, 283.0 ± 5.7 cm$^2 \cdot$kg^{-1} while the males were: age, 21.1 ± 0.6 yr; height, 178.6 ± 2.1 cm; weight, 75.6 ± 4.2 kg; body surface area, 1.93 ± 0.06 m^2; and A_D/wt, 258.9 ± 6.5 cm$^2 \cdot$kg^{-1}. All experiments were conducted during early spring months. Prior to the heat exposures all subjects underwent medical examination to determine their fitness for the study.

The nineteen male and female subjects, dressed in T-shirts, shorts, socks and indoor shoes, were then concurrently acclimatized for 6 consecutive days by walking on a level motor-driven treadmill at 1.34 m$\cdot$s^{-1} for two 50-min periods with a preceeding and intervening 10-min rest period, at 49°C, 20% rh, 1 m$\cdot$s^{-1} wind speed. After this acclimatization period, the subjects were exposed to six environmental and work load variations: a mild-wet climate ($T_a = 32^\circ$C, rh = 80%, $P_a = 28.5$ Torr, WBGT = 30.3°C), two hot-wet climates ($T_a = 35^\circ$C, rh = 90%, $P_a = 37.9$ Torr, WBGT = 34.0°C; $T_a = 37^\circ$C, rh = 80%, $P_a = 37.7$ Torr, WBGT = 34.5°C) and two hot-dry climates ($T_a = 49^\circ$C, rh = 20%, $P_a = 17.6$ Torr,

WBGT = 34.0°C; T_a = 54°C, rh = 10%, P_a = 11.3 Torr, WBGT = 34.2°C). Wind speed for all climates was constant at 1 m·s⁻¹. The WBGT was similar for the two hot-wet as compared to the two hot-dry environments. Each of these exposures lasted 120 min: 10' rest, 50' walk, 10' rest, 50' walk. Subjects walked at the same speed (1.34 m·s⁻¹) on a level treadmill during these five combinations and in addition walked at 1.34 m·s⁻¹ on a 5% grade during a second exposure to the 49°C, 20% rh condition.

During all heat exposures, rectal temperature (T_{re}) was recorded from a Y.S.I. rectal thermistor probe inserted ~ 10 cm beyond the anal sphincter. Skin temperatures were monitored with a three-point thermocouple skin harness (chest, calf and forearm) and mean weighted skin temperature ($\bar{T}_{sk}$) was calculated according to Burton (3). Using a Hewlett Packard 9825A Calculator and 9862A Plotter on-line during experimentation, both $\bar{T}_{sk}$ and T_{re} were plotted for each subject at approximately 2-min intervals. Heat storage (S) was calculated as follows: S = 0.965 (0.8 Δ T_{re} + 0.2 Δ $\bar{T}_{sk}$) in W·kg⁻¹. Heart rate was measured by radial artery palpation during the rest periods and after each 25 min of walking. Ad lib drinking was encouraged. At the end of the first rest period and at the end of each walking period, two-min expired air samples were collected in Douglas bags; the volume was measured in a Collins Spirometer and converted to standard environmental conditions (STPD), and the O_2 and CO_2 concentrations were measured with an Applied Electrochemistry Model S-3A O_2 analyzer and Beckman LB-2 infrared CO_2 analyzer. A time weighted average metabolic rate (M) was calculated as 0.17 of the resting value plus 0.83 of the mean of the two level walking values. In the case of walking uphill the external work was deducted from the measured metabolic rate (12). Total body weight losses were determined from pre- and post-walk measurements on a K-120 Sauter precision electronic balance (accuracy of ± 10 g) for calculation of sweat

rate. Sweat rate ($\dot{m}_{sw}$) was determined from weight loss, adjusted for water intake, urine output, and respiratory and metabolic weight losses. The metabolic weight loss ($\dot{m}_f$) and the respiratory water loss ($\dot{m}_e$) were calculated according to Mitchell et al. (8) as: $\dot{m}_f = 0.53 \, \dot{V}O_2$ in $g \cdot min^{-1}$ and $\dot{m}_e = 0.019 \, \dot{V}O_2 \, (44\text{-}P_a)$ in $g \cdot min^{-1}$, where P_a is the ambient water vapor pressure (mm Hg) and $\dot{V}O_2$ is the O_2 consumption ($l \cdot min^{-1}$). The net sweat rate was expressed as the theoretical evaporative cooling power (1 Watt = $1.486 \, g \cdot h^{-1}$), and normalized both per kg body weight and per m^2 surface area.

$\overline{T}_{sk}$ and $\Delta \, (T_{re}\text{-}\overline{T}_{sk})$ were calculated as mean values from the individual 2-min values starting from the 11th min of the exposure (the beginning of the 1st walking period) to the end of the exposure. Conductance was calculated as an average value for the last 20 min (when the subjects were either in or close to thermoequilibrium) as: Conductance $= (M - S)/(T_{re} - \overline{T}_{sk})$ in $W \cdot m^{-2} \cdot {}^{o}C^{-1}$. The radiative and convective heat exchange with the environment (R + C), the evaporative cooling power needed to maintain thermoequilibrium (E_{req}) and the maximal evaporative cooling power of the environment (E_{max}) were calculated according to Givoni and Goldman (6). In the calculation of R + C and E_{max}, the actual T_{sk} for each two min interval was used, and then the two min values were averaged to determine the mean value for the 120 min exposure. The evaporative heat loss (E) was calculated as E = M + (R + C) - S, and the heat loss by evaporation of sweat alone (E_{sw}) as $E_{sw} = E - E_{res}$, where E_{res} is the respiratory heat loss $E_{res} = 0.0023M \, (44 - P_a)$ (8). The efficiency of sweat evaporative cooling (μ) was determined as $\mu = E_{sw}/\dot{m}_{sw}$ with $\dot{m}_{sw}$ corrected as indicated above for respiratory and metabolic weight losses. Criteria for terminating any heat exposure were a heart rate of 180 beats$\cdot$min^{-1} during exercise or 140 beats$\cdot$min^{-1} during rest, and/or a T_{re} above $39.5^{o}C$, dizziness, nausea, or dry skin.

<u>Statistical Treatment</u>

Most variables were evaluated by use of a mixed design of two factors, with one factor being the two groups (male and female) and the other being the treatment (environmental conditions) which both groups received. If a significant F-value was found ($P < 0.05$), critical differences were analyzed by Tukey's procedure to locate the significant mean differences.

RESULTS

When the components of the heat balance equation were expressed in terms of power per unit body weight ($W \cdot kg^{-1}$), no differences between the sexes were found for metabolic heat production, radiative and convective heat exchange, and therefore in the E values either for HD or HW conditions (Table 1). However, for these same data, analysis per unit surface area ($W \cdot m^{-2}$) yielded sex-related differences as illustrated in Figures 1, 2 and Tables 1, 2. The metabolic rate was significantly lower ($P < 0.05$) for the females in all conditions (10-13% in HD and 13-15% for HW). The R + C was found to be 4-5% lower for the women in HD conditions, but significantly lower only for the 54°, 10% rh condition. In humid conditions, R + C was equal for both sexes when the value was positive ($37^\circ C$, 80% rh), but for the two HW conditions with negative R + C ($32^\circ C$, 80% rh; $35^\circ C$, 90% rh) a trend for higher R + C heat dissipation was found for men, although these differences were not statistically significant ($P > 0.05$). The E_{sw}, which reflects the combined effects of M and (R + C), was significantly lower ($P < 0.05$) for the women in all HD conditions and also for the HW condition at $32^\circ C$, 80% rh (9-13%). Women also displayed lower E_{sw} in the other two HW conditions, but these were not significantly lower. The $\dot{m}_{sw}$ was found to be significantly lower ($P < 0.05$) for the females (20-30% lower) for the

HW environments as illustrated in Figure 4. No significant differences in $\dot{m}_{sw}$ were found for the HD conditions as illustrated in Figure 3. No differences in sweat efficiency (μ) were found between the sexes in HD conditions, but the efficiency was higher for females in all HW conditions although significantly higher only in the most severe HW condition (37°C, 80% rh) as presented in Table 1.

An analysis of the heat transfer parameters (Table 2) showed a trend for higher $\bar{T}_{sk}$ in HD environments for the females ($0.3 - 0.6^{\circ}$C), with the difference being significantly higher ($P < 0.05$) only in the most severe exercise condition (49°C, 20% rh, 5% grade). Also, a trend of lower $\bar{T}_{sk}$ values for females prevailed in the HW conditions. The $T_{re} - \bar{T}_{sk}$ gradient was significantly lower for women in two of the HD conditions (not significant for 49°C; 20% rh, 0% grade), but there were no differences between the sexes in any of the HW conditions. The conductance, which ranged from 129 $W \cdot m^{-2} \cdot {}^{\circ}C^{-1}$ in the most severe exercise HD condition to 40 $W \cdot m^{-2} \cdot {}^{\circ}C^{-1}$ for 32°C, 80% rh, was found to be similar for both sexes. The demand for evaporative cooling rate to maintain thermoequilibrium (E_{req}) was significantly lower (10-14%) for the women under all conditions. However, no significant differences between the sexes were found for E_{max} nor for the index E_{req}/E_{max}. The thermoregulatory forcing function ($E_{req} - E_{max}$) suggested a higher surplus cooling power for females in HD conditions (significant only for 49°C, 20% rh, 5% grade) and no difference in HW conditions.

The comparisons between the sexes in heat balance components and in heat transfer parameters are summarized in Table 3. Women appear to have lower heat gain from the environment (lower R + C), as well as lower metabolic heat production and therefore have lower E_{sw} and E_{req} when all these values are calculated per unit surface area. Compared to men, the women's mean skin

temperature ($\overline{T}_{sk}$) tend to be higher in HD and lower in HW conditions. Their core-to-skin temperature gradient is smaller than the males in HD conditions (equal in HW), but their conductance is essentially the same. Women are also seen to have a higher cooling surplus (E_{req} - E_{max}) under HD conditions.

DISCUSSION

The major objective of this study was to evaluate sex differences in heat balance and transfer for various climatic conditions. For this purpose, three HD and three HW conditions were chosen. For the HD conditions the initial environment for evaluation was 49°C and 20% rh, from which the total heat load was increased once by elevating the ambient temperature to 54°C so that (R + C) was increased by 50%, and once by increasing the metabolic heat production by 50% (walking on a 5% grade instead of on the level). For the HW conditions, the first condition (35°C, 90% rh) was chosen such that the T_a was close to the $\overline{T}_{sk}$. Thus, (R + C) would be minimal and the WBGT would be similar to that of the HD conditions. The other two HW conditions were chosen to produce either a small positive R + C (37°C, 80% rh) or a small negative R + C (32°C, 80% rh).

The difference in body size between the sexes, with a lower body weight and surface area but a higher surface area-to-mass ratio for women, is well known (11), and is consistent with our sample, which represents a young military population (18). Thus, a major methodological problem arose involving whether to express the heat balance components in units of power per body weight or per surface area. We observed similar results for both sexes when the heat balance parameters were expressed per unit body weight; in contrast sex-related differences were found when these parameters were analyzed per unit surface area.

It would seem more logical to compare these heat balance values when they are presented per unit body surface area for a variety of reasons. Of the two heat gain components M and $(R + C)$, only the first (M) relates heat production to proportion of body mass, while the other $(R + C)$ is surface area related. Since heat dissipation is proportional to the surface area, and the crucial problem in hot environments is heat dissipation, it would seem preferable to use heat balance values per surface area as expressions to normalize differences between individuals.

The conclusive terms for heat dissipation are the E_{sw}, which is the actual heat dissipation provided by sweat evaporation, and the E_{req}, which denotes the required evaporative cooling power for thermoequilibrium. In this study, both E_{sw} and E_{req} were lower for the females than for the males (9 - 14%) under all conditions when expressed per surface area. However, the difference in E_{sw} was significantly lower in the HW conditions only for $32^{\circ}C$, 80% rh. Examination of the two main components of E_{sw} and E_{req} (M and $R + C$) showed that these differences were mainly due to the lower metabolic heat production of the females (as expected since the females weighed less and the metabolism per unit body weight was similar for both sexes). However, the heat production was "spread" over a proportionately higher surface area in the females, i.e., the differences in heat production are greater than the differences in surface area. According to the literature (4, 11, 14), the other main component of E_{sw} and E_{req}, which is $R + C$, might be a disadvantage for females in HD conditions due to their higher A_D/wt, and therefore higher surface area available for absorbing heat from the environment by radiation and convection when air temperature is much above skin temperature. Our findings showed that the higher A_D/wt for the females was not a disadvantage since they gained similar heat by radiation and convection per unit body weight as the males, but gained 4 - 5% less per unit

surface area. The latter was found to be significant in the most severe HD condition (54°C, 10% rh), where the greatest disadvantage for a higher A_D/wt would be expected. The higher $\bar{T}_{sk}$ for the females exhibited in these HD environments appears to be responsible for the lower R + C gain than what would be expected. Since R + C is proportional to the $T_a - \bar{T}_{sk}$ difference, increasing $\bar{T}_{sk}$ would effectively decrease R + C heat gain.

The higher skin temperature for the females under HD conditions would decrease the T_{re} to $\bar{T}_{sk}$ gradient, which is a major factor in transferring heat from the core to the periphery, resulting in an increased conductance (10). In this study despite the above mentioned decrease in the T_{re} to $\bar{T}_{sk}$ gradient, a similar conductance was found for both sexes. These findings can be related to the lower M/A_D for the females and the ability to conduct the same amount of heat with a lower gradient using a proportionately higher surface area.

Under the HW conditions where (R + C) was less important, the females showed a trend for a lower $\bar{T}_{sk}$, higher T_{re} to $\bar{T}_{sk}$ gradient, and lower conductance than the males; however, it was only a trend, without any significant differences. Under the same HW environmental conditions the females better suppressed the nonevaporative sweat as shown by a lower $\dot{m}_{sw}$ and higher μ, both differences significant for the 37°C, 80% rh condition. This phenomenon was discussed extensively in a previous paper (15).

The E_{req}/E_{max} ratio, which is related to percent of skin wettedness when the index is below 1 and represents sweat dripping from the skin when it is close to or above 1 (6), can be used as a rough index of heat distress in hot environments. This ratio was found to be similar for both sexes under all 6 conditions and was found to express similar environmental comfort or discomfort for men and women under HD and HW conditions. Values of this index, along with the thermoregulatory forcing function ($E_{req}-E_{max}$) and the efficiency of

sweat evaporative cooling (μ) suggest a better overall state for the females; they have higher cooling surplus ability under HD climates (lower $E_{req}-E_{max}$; $P < 0.05$ for 49°C, 20% rh, 5% grade) and also a better suppression of nonevaporative sweat (higher μ) under HW climates ($P < 0.05$ for 37°C, 80% rh).

It is suggested that both sexes have qualitatively similar heat balance and heat transfer characteristics. The differences are basically quantitative, where the females' higher surface area-to-mass ratio is a decided advantage in both hot-dry and hot-wet environments. In hot-dry conditions where (R + C) is a major factor, the physiological mechanism which protects women against the expected excessive heat gain by convection and radiation due to their higher A_D/wt is their increased skin temperature.

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TABLE 1. Comparison of heat balance components of the various climatic conditions (mean ± SE) for males (M) and females (F)

	HOT-DRY						HOT-WET					
T_a °C, rh %	49°C, 20%		54°C, 10%		49°C, 20%		32°C, 80%		35°C, 90%		37°C, 80%	
	M	F	M	F	M	F	M	F	M	F	M	F
Treadmill grade %	0		0		5		0		0		0	
R + C, W·m^{-2}	128 ± 3	123 ± 2	188 ± 2	178* ± 1	139 ± 2	133 ± 2	-23 ± 1	-18 ± 2	-6 ± 1	-2 ± 1	15 ± 1	17 ± 1
R + C, W·kg^{-1}	3.31 ± 0.12	3.48 ± 0.09	4.86 ± 0.09	5.05 ± 0.14	3.60 ± 0.08	3.78 ± 0.10	-0.60 ± 0.04	-0.52 ± 0.06	-0.16 ± 0.02	-0.07 ± 0.03	0.40 ± 0.02	0.47 ± 0.02
M, W·m^{-2}	169 ± 5	152* ± 4	171 ± 3	152* ± 3	232 ± 7	201* ± 4	172 ± 4	146* ± 5	179 ± 4	154* ± 4	174 ± 4	151* ± 4
M, W·kg^{-1}	4.37 ± 0.12	4.28 ± 0.10	4.43 ± 0.11	4.31 ± 0.11	5.98 ± 0.12	5.69 ± 0.12	4.44 ± 0.12	4.11 ± 0.12	4.64 ± 0.16	4.36 ± 0.09	4.51 ± 0.18	4.26 ± 0.10
E_{sw}, W·m^{-2}	277 ± 6	254* ± 5	333 ± 4	295* ± 7	340 ± 7	313* ± 4	135 ± 5	119* ± 7	144 ± 4	134 ± 3	159 ± 4	145 ± 3
E_{sw}, W·kg^{-1}	7.15 ± 0.20	7.19 ± 0.15	8.61 ± 0.20	8.36 ± 0.25	8.77 ± 0.19	8.84 ± 0.14	3.50 ± 0.12	3.36 ± 0.15	3.73 ± 0.12	3.78 ± 0.11	4.13 ± 0.18	4.11 ± 0.13
$\dot{m}_{sw}$, W·m^{-2}	314 ± 12	291 ± 10	368 ± 15	368 ± 16	402 ± 21	351 ± 10	179 ± 11	145* ± 9	355 ± 27	287* ± 14	360 ± 17	256* ± 20
$\dot{m}_{sw}$, W·kg^{-1}	8.12 ± 0.33	8.23 ± 0.37	9.48 ± 0.35	10.41 ± 0.51	10.39 ± 0.56	9.95 ± 0.39	4.58 ± 0.21	4.07 ± 0.21	9.16 ± 0.69	8.10 ± 0.42	9.29 ± 0.43	7.23* ± 0.58
μ	0.89 ± 0.03	0.88 ± 0.04	0.92 ± 0.03	0.82 ± 0.04	0.86 ± 0.03	0.90 ± 0.08	0.78 ± 0.04	0.84 ± 0.05	0.43 ± 0.03	0.47 ± 0.02	0.45 ± 0.02	0.59* ± 0.04

*P < 0.05 (for M vs F differences)

TABLE 2. Comparison of heat transfer parameters in the various climatic conditions (mean ± SE) for males (M) and females (F)

	HOT-DRY						HOT-WET					
T_a °C, rh %	49°C, 20%		54°C, 10%		49°C, 20%		32°C, 80%		35°C, 90%		37°C, 80%	
	M	F	M	F	M	F	M	F	M	F	M	F
Treadmill grade %	0		0		5		0		0		0	
$\bar{T}_{sk}$, °C (mean of 11'-120')	35.9 ± 0.1	36.4 ± 0.2	36.0 ± 0.2	36.3 ± 0.2	35.7 ± 0.2	36.3* ± 0.2	34.2 ± 0.2	33.8 ± 0.2	35.9 ± 0.1	35.5 ± 0.1	36.2 ± 0.1	36.0 ± 0.1
$T_{re} - \bar{T}_{sk}$, °C (mean of 11'-120')	1.74 ± 0.18	1.31 ± 0.19	1.43 ± 0.14	0.67* ± 0.14	2.13 ± 0.27	1.60** ± 0.17	3.40 ± 0.15	3.77 ± 0.18	2.01 ± 0.07	2.22 ± 0.09	1.92 ± 0.06	1.90 ± 0.06
Conductance, $W \cdot m^{-2} \, °C^{-1}$ (last 20')	107 ± 10	105 ± 10	114 ± 12	116 ± 13	126 ± 17	129 ± 11	51 ± 3	40 ± 2	82 ± 5	63 ± 5	89 ± 4	73 ± 5
E_{req}, $W \cdot m^{-2}$	297 ± 5	267* ± 6	362 ± 4	329* ± 5	350 ± 7	308* ± 4	149 ± 4	129* ± 7	172 ± 4	152* ± 4	188 ± 4	166* ± 3
E_{max}, $W \cdot m^{-2}$	439 ± 6	431 ± 6	524 ± 7	503 ± 7	404 ± 9	399 ± 7	197 ± 5	168 ± 6	116 ± 3	95 ± 4	137 ± 3	122 ± 3
E_{req}/E_{max}	0.68 ± 0.02	0.62 ± 0.02	0.69 ± 0.01	0.65 ± 0.02	0.87 ± 0.03	0.77 ± 0.02	0.76 ± 0.03	0.78 ± 0.07	1.49 ± 0.04	1.62 ± 0.09	1.38 ± 0.04	1.36 ± 0.04
$E_{req} - E_{max}$, $W \cdot m^{-2}$	-142 ± 9	-164 ± 11	-163 ± 9	-174 ± 11	-54 ± 14	-91* ± 8	-48 ± 8	-40 ± 12	56 ± 4	56 ± 5	52 ± 5	43 ± 4

* $P < 0.05$ (for M vs F differences)

** $P < 0.06$

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TABLE 3. Summary of sex-related trends in heat transfer under hot-dry and hot-wet climates

	hot dry	hot wet
$R + C$		= or
M		
E_{sw}		
$\dot{m}_{sw}$	= or	
μ	=	
$\bar{T}_{sk}$		= or
$T_{re} - T_{sk}$		=
Conductance	=	= or
E_{req}		
E_{max}	=	=
E_{req}/E_{max}	=	=
$E_{req} - E_{max}$		=

= No difference

Females are lower than males

Females are higher than males

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FIGURE LEGENDS

FIG. 1   Comparison of mean E, (E = M + (R + C) - S) between males (M) and females (F) in three hot-dry conditions (49°C, 20% rh walking level; 54°C, 10% rh walking level; 49°C, 20% rh walking 5% grade). The numbers at the top of each column represent the E values. The area (R + C and S) above and below the zero point represent whether these values are to be added or subtracted from M.

FIG. 2   Comparison of mean E, (E = M + (R + C) - S) between males (M) and females (F) in three hot-wet conditions (32°C, 80% rh; 35°C, 90% rh; 37°C, 80% rh). The numbers at the top of each column represent the E values. The areas (R + C and S) above and below the zero point represent whether these values are to be added or subtracted from M.

FIG. 3   Comparison of mean sweat rate ($\dot{m}$) and evaporative heat loss (E) between males (M) and females (F) in three hot-dry conditions (49°C, 20% rh walking level; 54°C, 10% rh walking level; 49°C, 20% rh walking 5% grade). Significant difference between sexes indicated by an asterisk.

FIG. 4   Comparison of mean sweat rate ($\dot{m}$) and evaporative heat loss (E) between males (M) and females (F) in three hot-wet conditions (32°C, 80% rh; 35°C, 90% rh; 37°C, 80% rh). Significant difference between sexes indicated by an asterisk.
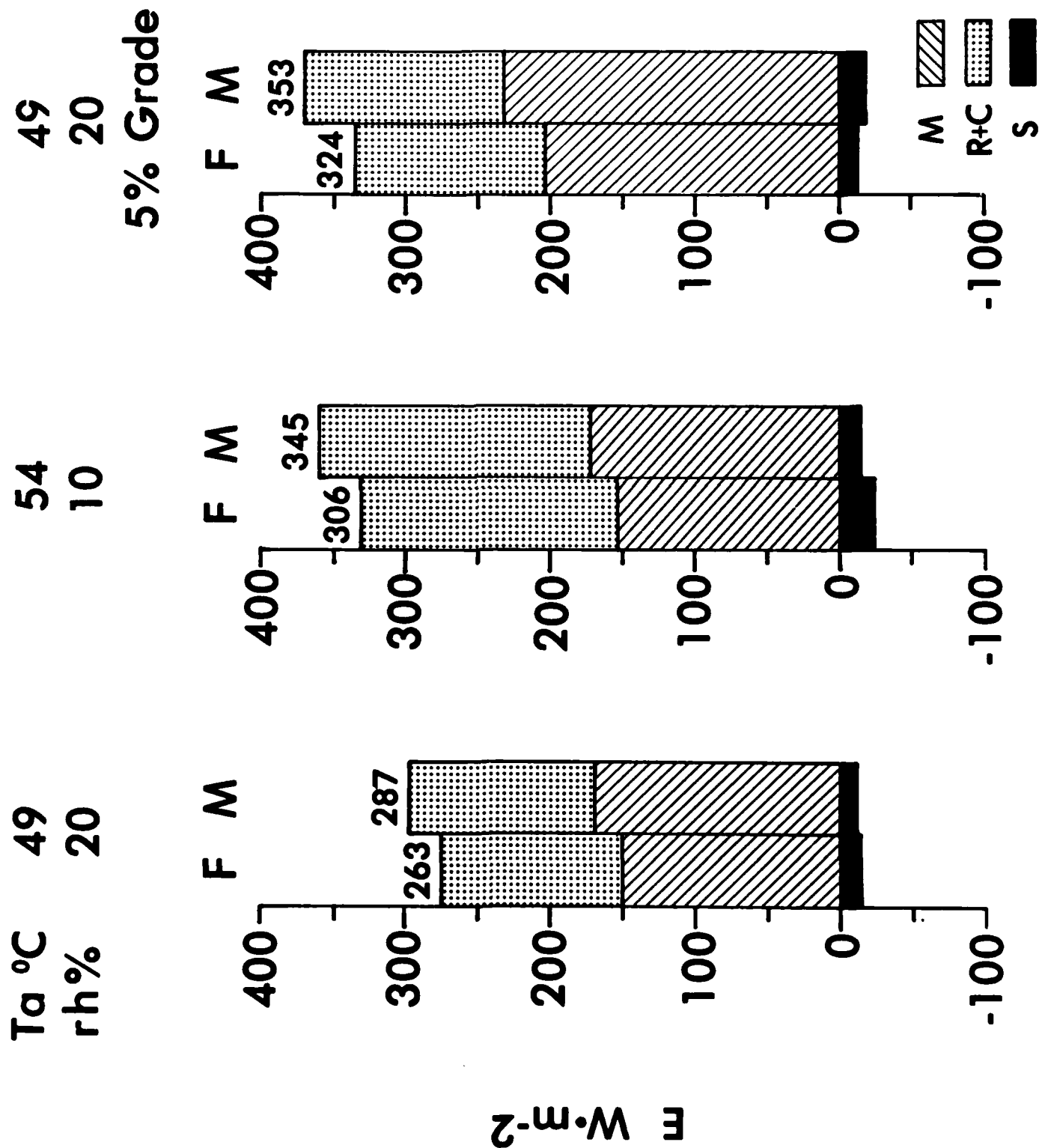
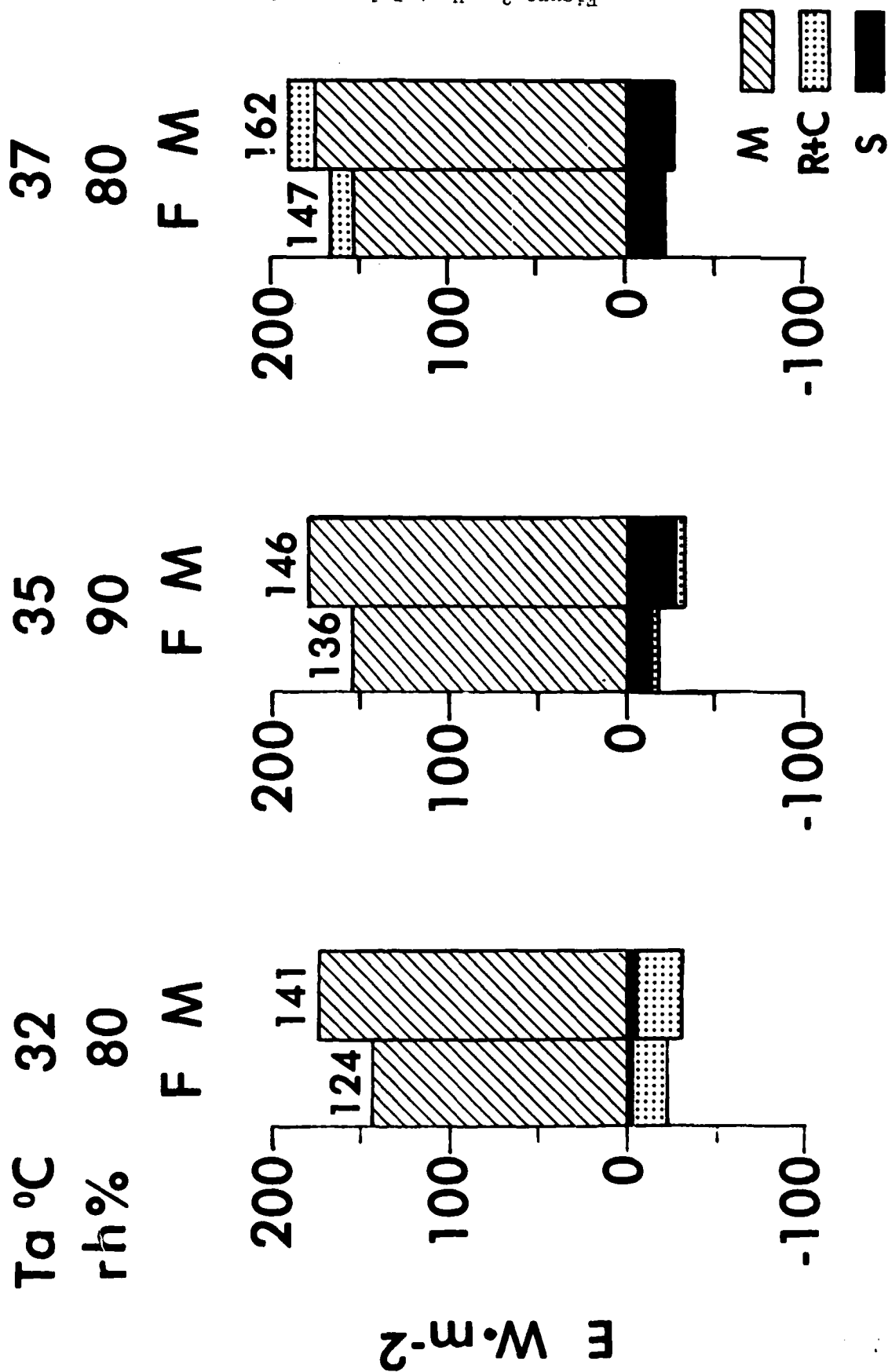Figure 1 – Heat Balance and Transfer
of Men and Women

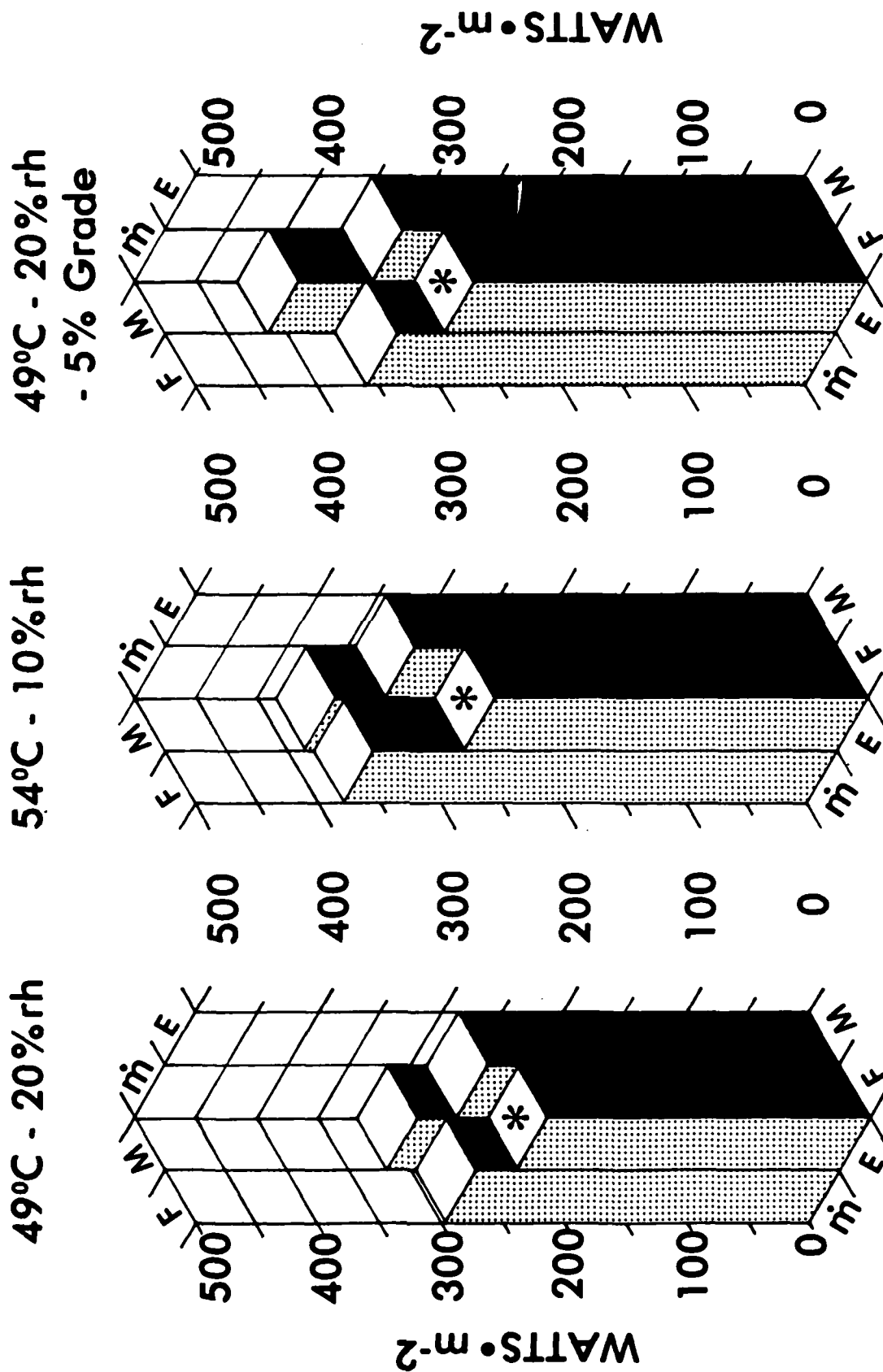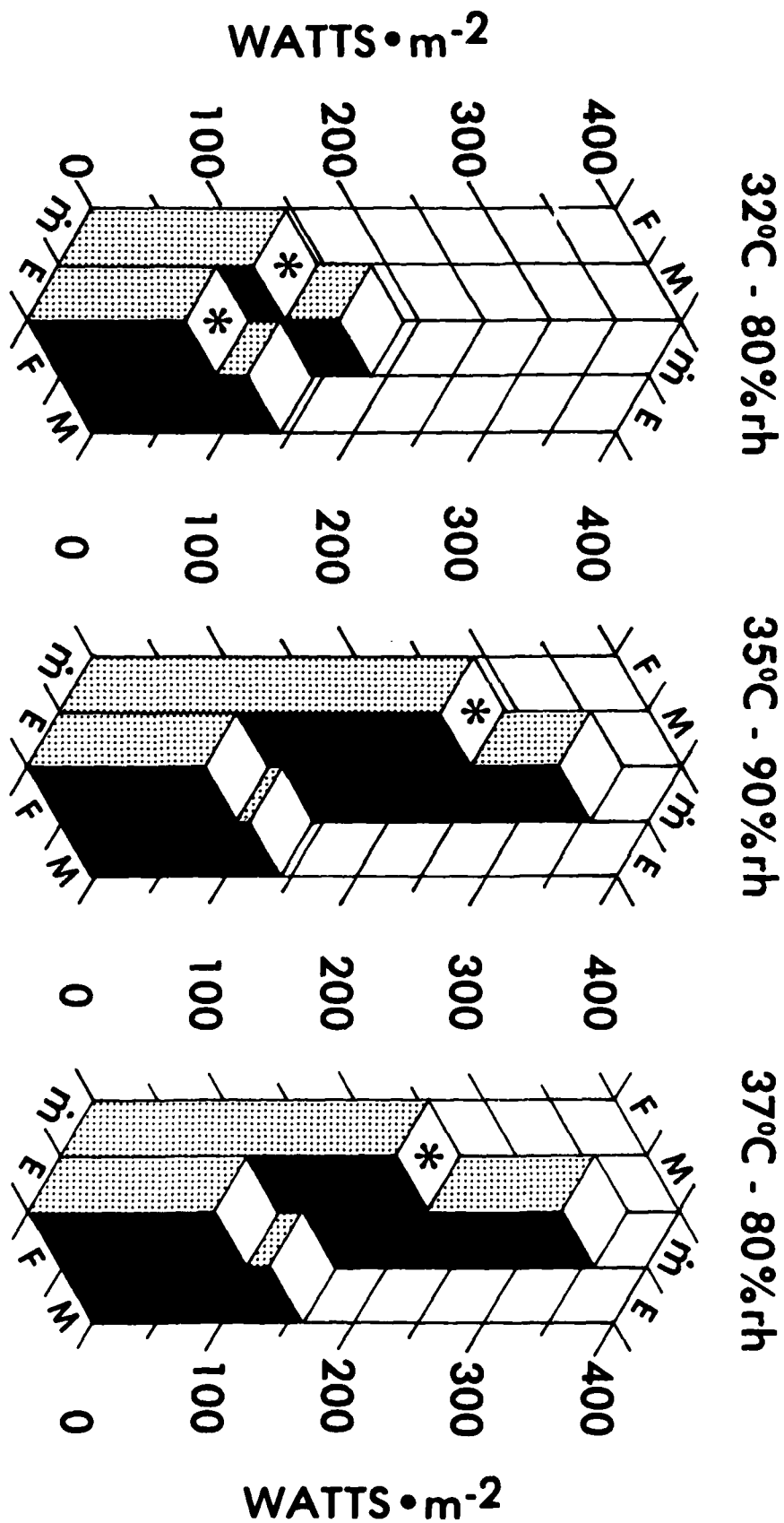Figure 2 - Heat Balance and Transfer
of Men and Women

Figure 3 — Heat Balance and Transfer
of Men and Women

Figure 4 – Heat Balance and Transfer
of Men and Women

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PREDICTING SWEAT RATE RESPONSE TO EXERCISE, ENVIRONMENT AND CLOTHING

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Running Head: Prediction of sweat rate

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ABSTRACT

Metabolic heat production (M), clothing heat transfer characteristics, and the environment dictate a required evaporative cooling (E_{req}) from the body to maintain thermal balance. However, the maximal evaporative capacity (E_{max}) is dictated by vapor transfer properties of the clothing and environment. Relationships between metabolic load, environmental conditions, clothing and sweat loss were studied in 34 heat acclimatized males categorized into 4 groups (8, 8, 8, and 10 subjects) and exposed to various environmental conditions (T_a, 20 - 54°C, and rh, 10 - 90%), levels of metabolic rate (resting; walking 1.34 m • s^{-1}, level; and walking 1.34 m • s^{-1}, 5% grade) while wearing various clothing ensembles (shorts and T-shirts, fatigues, fatigues plus overgarment, and sweat suit). Each group was not exposed to all combinations. Exposures lasted 120 min: either 10 min rest, 50 min exercise, 10 min rest, 50 min exercise, or 120 min at rest. Physiological measurements included heart rate, rectal temperature, mean skin temperature, energy expenditure and sweat loss ($\dot{m}_{sw}$). E_{max} and E_{req} were calculated from environmental conditions, metabolism, clothing insulation and permeability. The ratio E_{req} to sweat rate was found to correlate with E_{max} and not with M. The predictive equation for sweat rate was: $\dot{m}_{sw} = 27.9 • E_{req} • (E_{max})^{-0.455}$; g•m^{-2}•h^{-1} within the limits: $50 < E_{req} < 360$; $20 < E_{max} < 525$, W•m^{-2}. This formula predicts sweat loss under different work loads and climates.

Index items: sweat loss; required evaporative cooling; maximal evaporative capacity; humid and dry heat; heat transfer; clothing insulation and permeability; metabolism; heart rate; skin temperature; rectal temperature.
INTRODUCTION

INTRODUCTION

Metabolic heat production (M) and heat gain from the environment by radiation and convection (R + C) determine the required evaporative cooling (E_{req}) from the body in order to maintain thermal balance ($E_{req} = M \pm (R + C)$). The major source for evaporative cooling is sweat since, in man, respiratory evaporation contributes to a minor degree in warm and hot conditions. Thus, if the efficiency of sweat evaporation were 100% then the sweat rate would be equal to E_{req} with the assumption that heat storage is zero.

For an efficiency of 100% it is necessary that the total amount of sweat produced be evaporated, and all the evaporative heat be taken from the body. It is obvious that under hot-dry conditions the efficiency will be close to 100% and the sweat rate will be close to the E_{req} (14). However, in humid conditions the skin is wet, some of the sweat drips off the skin and the efficiency of sweating is low; therefore, the sweat rate is higher than E_{req}.

Since core temperature, skin temperature and skin wettedness are the main inputs to the thermoregulatory center, and the sweat glands are major thermo-regulatory effectors in hot environments, the sweat glands will receive more impulses with increases in heat production or storage (1, 13), and inhibitory feedback by skin wettedness and decreases in skin temperature (3, 5, 16). It can be assumed, therefore, that sweat production should be correlated with E_{req} (heat production and R + C heat exchange), and with the maximal evaporative capacity of the environment (E_{max}) which together with the E_{req} will dictate the wettedness of skin (E_{req}/E_{max} determines skin wettedness).

The three main attempts to predict sweat rate are based on the above assumptions. The predicted 4-hour sweat rate index (P4SR) (15) which is derived

from the nomogram for the basic 4-hour sweat rate (B4SR) involves air temperature, wet-bulb temperature, air speed and a correction for the type of clothing. These factors are used for determining the E_{max} and then subsequently the B4SR from which the P4SR is calculated taking into consideration the metabolic rate (the major contributor to E_{req}). The Givoni prediction model (11) is based on an exponential function of the ratio E_{req}/E_{max}. Lustinec's models (14) are based on the linear correlation between sweat rate and E_{req} for low skin wettedness, but uses a non-linear correlation between sweat rate, E_{req} and E_{max}, when the skin wettedness is high. The above models are not totally comprehensive. The P4SR is limited to air temperatures above $27^{\circ}C$ and to low relative humidity. Givoni's model is limited to $E_{req}/E_{max} < 1$, and Lustinec's model to E_{req} lower than $100 \ W \cdot m^{-2}$ when E_{max} is lower than $100 \ W \cdot m^{-2}$, and for E_{req} lower than $300 \ W \cdot m^{-2}$ when E_{max} is lower than $200 \ W \cdot m^{-2}$.

The purpose of this study was to develop a comprehensive mathematical model to predict sweat rate for a wide range of environmental conditions, energy expenditures and clothing ensembles.

METHODS

Thirty-four male volunteer soldiers served as subjects. All subjects were totally informed with regard to experimental risk and gave their written informed consent. The subjects were divided into three experimental series, where the first series was composed of three groups, 8 subjects each; the second series of 10 subjects, and the third of 8 who had participated also in the second series. The physical characteristics of the subjects in the first group of the first

series were: age, 22.1 ± 1.0 yr; weight, 71.3 ± 4.4 kg; height, 176.4 ± 4.0 cm; body fat, $18.3 \pm 1.7\%$; the second group: age 21.8 ± 0.8 yr; weight, 72.8 ± 3.0 kg; height, 173.2 ± 2.3 cm; body fat, $18.7 \pm 1.4\%$; the third group: age, 22.1 ± 0.6 yr; weight, 72.9 ± 3.4 kg; height 177.4 ± 2.3 cm; body fat, $14.9 \pm 1.1\%$. The physical characteristics ror the subjects of the second series were: age, 21.1 ± 0.6 yr; weight 75.6 ± 4.2 kg; height, 178.6 ± 2.1 cm; body fat, $17.7 \pm 1.6\%$; and for the third series were: age, 20.9 ± 0.6 yr; weight, 75.3 ± 5.5 kg; height, 178.2 ± 2.5 cm; body fat, $17.3 \pm 1.9\%$.

Prior to the heat exposures all subjects underwent medical examinations to determine their fitness for the study. The thirty-four subjects, dressed in T-shirts, shorts, socks and indoor shoes, were then acclimatized for 6 consecutive days by walking on a level motor-driven treadmill at $1.34 \text{ m} \cdot \text{s}^{-1}$ for two 50-min periods with both a preceding and intervening 10-min rest period, at 49°C, 20% rh, $1 \text{ m} \cdot \text{s}^{-1}$ wind speed. After this acclimatization period, the subjects were exposed to the various environmental, work and clothing variations as is described in Tables 1 and 2.

Each exposure lasted 120 min: 10 min rest, 50 min walk, 10 min rest, 50 min walk, or 120 min continuous rest for the resting group. During all heat exposures, rectal temperature (T_{re}) was recorded from a Y.S.I. rectal thermistor probe inserted ~ 10 cm beyond the anal sphincter. Skin temperatures were monitored with a three-point thermocouple skin harness (chest, calf and forearm) and mean weighted skin temperature ($\bar{T}_{sk}$) was calculated according to Burton (4). Using a Hewlett-Packard 9825A Calculator and 9826A Plotter on line during experimentation, both $\bar{T}_{sk}$ and T_{re} were plotted for each subject at approximately 2-min intervals. Heart rate was measured by radial artery palpation during the rest periods and after each 25 min of walking. Ad lib water

drinking was encouraged. At the end of the first rest period and at the end of each walking period, two-min expired air samples were collected in Douglas bags; the volume was measured in a Collins Spirometer and converted to standard environmental conditions (STPD), and the O_2 and CO_2 concentrations were measured with an Applied Electrochemistry Model S-3A O_2 analyzer and Beckman LB-2 infrared CO_2 analyzer. A time-weighted average metabolic rate (M) was calculated as 0.17 of the resting value plus 0.83 of the mean of the two level walking values. In the case of walking uphill, the external work was deducted from the measured metabolic rate (18). Total body weight losses were determined from pre- and post-walk measurements on a K-120 Sauter precision electronic balance (accuracy of $\pm$ 10 g) for calculation of sweat rate. Sweat rate ($\dot{m}_{sw}$) was determined from weight loss, adjusted for water intake and urine output. The sweat rate was expressed as the theoretical evaporative cooling power (1 watt = 1.486 g $\cdot$ h^{-1}), and normalized per m^2 surface area.

The radiative and convective heat exchange with the environment (R + C), the evaporative cooling power needed to maintain thermoequilibrium (E_{req}) and the maximal evaporative cooling power of the environment (E_{max}) were calculated according to Givoni and Goldman (9, 10) and normalized per m^2 surface area.

The values for insulation (clo) around the man (total clo as measured by heated copper manikin) were: 0.74, 0.99, 1.50 and 1.20 for shorts and T-shirt, fatigues, fatigues plus overgarment and plastic sweat suit, respectively. The corresponding values for the permeability index of the clothing (i_m/clo) were: 0.94, 0.75, 0.51 and 0.20, respectively. Criteria for terminating any heat exposure were a HR of 180 beats$\cdot$min^{-1} during exercise, or of 140 beats$\cdot$min^{-1} during rest, and/or a T_{re} above 39.5°C, dizziness, nausea, or dry skin.

Statistical Treatment

The differences in $E_{req}/\dot{m}_{sw}$ ( ) were analyzed by using a mixed-factorial analysis with each subject receiving all combinations of factors (clothing and environmental conditions), but where the subjects are divided into groups by level of metabolism (rest, walking level and walking upgrade). If a significant F-value was found ($p < 0.05$), critical differences were calculated by Tukey's procedure to locate the significant mean differences. The power curve fit ($y = ax^b$) was calculated as a linear regression of the logarithmic expression $\ln y = \ln a + b \ln x$. In a similar way the exponential curve fit ($y = ae^{bx}$), the logarithmic curve fit ($y = a + b \ln x$), the parabolic curve fit ($y = a + bx + cx^2$), and $y = a + b/x$, $1/y = a + b/x$ and $y = a + b \, x$ were all examined, as well as the associated linear regressions.

RESULTS

Development of the basic sweat rate model

Analysis of the 111 exposures from the first series of experiments (Table 1) yielded a similar $E_{req}/\dot{m}_{sw}$ index ( ) ($p > 0.05$) for the same combinations of clothing and environmental conditions (similar E_{max}), regardless of the level of energy expenditure (different E_{req}). However, the index ( ) was different and highly significant ($p < 0.001$) for different E_{max} either when the change in E_{max} was a result of different environmental conditions (wet vs dry) or due to different clothing ensembles (change in i_m/clo). The relationship between $E_{req}/\dot{m}_{sw}$ ( ) and E_{max} for these data of the first experimental series was found to be $= 0.0530 \, E_{max}^{0.452}$; $r = 0.87$ when E_{req}, E_{max} and the sweat rate were expressed in $W \cdot m^{-2}$ (See Figures 1,2). It can be seen that the above

mathematical formula used to express these data appears to be accurate for both the individual and the group responses in this first series of experiments.

The sweat rate can be derived from the above as:

$$\dot{m}_{sw} = 28.3\, E_{req} \cdot (E_{max})^{-0.452}; \; g \cdot m^{-2} \cdot h^{-1}$$

limited to the range: $135 < E_{max} < 430;\; 60 < E_{req} < 340;\; W \cdot m^{-2}$. The correlation between the predicted and the measured sweat loss for the first experimental series was found to be $r = 0.94$ as illustrated in Figure 3 and represents a wide range of sweating responses.

Expansion of the basic sweat rate model

In the 132 exposures of the second and third series (Table 2), the model was examined for a wider range of sweating responses than in the first series. High humidities and low permeable clothing (fatigue plus overgarment, and sweat suit) were used to challenge the model in the low range of E_{max}, down to 20 $W \cdot m^{-2}$, and through the use of both a hot and very dry environment (49°C; 20% rh and 54°C; 10% rh) up to 525 $W \cdot m^{-2}$. Additional challenges were posed when the E_{req} was reduced to 52 $W \cdot m^{-2}$ by exposure to a cool environment (20°C; 40% rh), and to 78 $W \cdot m^{-2}$ by resting in an air temperature close to skin temperature. Expanding the limits of sweating responses in these ways yielded values ranging from 0.22 ± 0.02 to 0.94 ± 0.03.

A comprehensive analysis of the relationship between   and E_{max} for all three experimental series left the original equation, derived from the first series, basically unchanged as illustrated in Figure 4 ($= 0.0537\, E_{max}^{0.455}$; $r = 0.95$). Therefore,

$$\dot{m}_{sw} = 27.9 \cdot E_{req} \cdot (E_{max})^{-0.455}; \; g \cdot m^{-2} \cdot h^{-1}$$

bounded by conditions of: $50 < E_{req} < 360;\; 20 < E_{max} < 525,\; W \cdot m^{-2}$.

Comparison of the present model with other models

Comparing the results from the present study with those of Lustinec's, or Givoni's or the P4SR models (Tables 1, 2 and Figure 5) shows that in the present model only one condition (sweat suit, walking in 37°C, 80% rh), out of the 30 that were examined, resulted in predicted sweat rates which differed by more than 20% from the measured. In the other 29 conditions, the predicted sweat rate was within the $\pm$ 20% range; the relationship found was: predicted $\dot{m}_{sw}$ = 3 + 0.98 measured $\dot{m}_{sw}$, r = 0.95. In Lustinec's model, eight conditions out of the 30 were out of the $\pm$ 20% range and in another four conditions, the sweat rate could not be predicted because the conditions were beyond the model's range (see Table 2). Using the present data and Lustinec's model, it was found that the predicted $\dot{m}_{sw}$ = 46 + 0.72 measured $\dot{m}_{sw}$, r = 0.93 (14). In Givoni's model, 14 conditions were out of $\pm$ 20% range while it was determined that for the present data using Givoni's model, predicted $\dot{m}_{sw}$ = 151 + 0.38 measured $\dot{m}_{sw}$, r = 0.51 (11). The largest deviations for this model from measured were found when E_{req} was close to or above E_{max}. For the P4SR model in 12 conditions the predicted sweat rate was beyond the $\pm$ 20% range while in two other conditions the sweat rate could not be predicted because the conditions were out of the P4SR model's range; it was found that predicted $\dot{m}_{sw}$ = -113 + 1.34 measured $\dot{m}_{sw}$ with an r = 0.83 (15).

Verification of the present model with results of other authors

Comparing the predicted sweat rate using the present model with the measured data from various other studies (Table 3) shows that in most cases the present equation predicts sweat rate within the range of $\pm$ 20%. Exceptions involved the very low sweat rates found in the Royal Naval Tropical Research Unit experimental series (predicted 102 $g \cdot m^{-2} \cdot h^{-1}$ vs 71 measured), and an overestimation of 33% in a study by Gonzalez et al. (12) where the sweat rate

was expressed as net evaporative sweat rate (weight loss minus respiratory weight loss, metabolic weight loss and dripping of sweat).

DISCUSSION

Physiological parameters like core temperature, skin temperature and skin wettedness influence the sweat rate (2, 3, 6, 16). These parameters together with heat storage, metabolic rate and an internal set-point can explain the different physiological models and pathways of sweat regulation (1, 13). Although these models are essential for understanding various thermoregulatory mechanisms, their applicability for prediction of sweat rate is limited because physiological measurements under actual exposures are needed to predict the sweat rate. In our previous studies, it was shown that body temperatures and heart rate are predictable by comparing the demand for heat loss with the capacity for heat loss, using the two main variables of thermoregulation, the overall heat load (E_{req}) and the maximal evaporative cooling capacity of the environment (E_{max}) (9, 10). Skin wettedness, as originally defined by Gagge (7), is simply the ratio of E_{req} to E_{max} and this same ratio is widely used directly as a heat stress index (HSI) in industry. Since the sweat rate depends on body temperatures, skin wettedness, metabolic rate (a parameter of E_{req}) and heat storage (a function of body temperatures) it can be assumed that the sweat rate can be derived directly from E_{req} and E_{max} without the need to measure the different physiological variables. The advantage of this assumption is obvious, because both E_{req} and E_{max} can be calculated directly from the environmental conditions, the predicted exercise intensity and the type of clothing without the need to make any physiological measurements. Thus, sweat rate can be predicted (at least $\pm$ 20 %) without the need to make physiological measurements.

The theoretical need of sweat evaporative cooling is a linear function of E_{req} (sweat rate = k $\cdot$ E_{req}, where k is the latent heat evaporation of water).

For a nude man, under conditions of low skin wettedness where the evaporation of sweat is practically unlimited, the sweat rate can be predicted using the above equation as was previously done in Lustinec's model for low skin wettedness (14). On the other hand, under other conditions where E_{max} is low or close to E_{req}, and the skin is wet, only part of the sweat is evaporated, while the rest of the sweat being produced is dripping or soaking the clothing, and therefore, the sweat rate will be higher than $k \cdot E_{req}$. Because E_{max} is the major factor in determining the evaporation rate and level of skin wettedness, it should be a part of any sweat rate prediction formula for clothed men or conditions of high skin wettedness.

In the present study, it was found that the efficiency of sweat was correlated with E_{max}; as expected, the efficiency was high for high evaporative cooling capacity and low for low E_{max}. The relationship between sweat rate, E_{req} and E_{max} was found empirically to be: $\dot{m}_{sw} = 27.9 \cdot E_{req} \cdot (E_{max})^{-0.455}$ in $g \cdot m^{-2} \cdot h^{-1}$; E_{req} and E_{max} in $W \cdot m^{-2}$. For high E_{max} (dry skin), the above formula is very close to $\dot{m}_{sw}$ = latent heat $\cdot E_{req}$ as expected. In contrast, the lower the E_{max}, the greater is its influence on the final values for the predicted sweat rate.

The present formula was derived from 250 exposures to a wide range of environmental conditions (cool, warm, hot, dry and humid) with a variety of clothing ensembles (light clothing, heavy clothing, high permeability and low permeability) and different metabolic rates (rest, 300 and 450 W). Therefore, our prediction equation can be used for a wide range of E_{req} (50 - 360 $W \cdot m^{-2}$) and of E_{max} (20 - 525 $W \cdot m^{-2}$). The verification of the present model using results published by other investigators (Table 3) supports this suggestion. The main limitation for the present prediction model appears to be at very high

sweat rates. In this case, the formula appears to overestimate the sweat rate; in one exposure in our study, when the measured sweat rate was 932 $g \cdot m^{-2} \cdot h^{-1}$, the predicted value was 1190 (overestimation of 28%). In this condition, it can be assumed that the actual sweat rate was close to the maximal sweat rate, so the sweating mechanisms were saturated (6) and subjects could not "reach" the values predicted as required to achieve a steady state thermoequilibrium (9, 10).

In general, however, we suggest that sweat rate can be predicted simply as a function of E_{req} and E_{max} for a wide range of climatic conditions, clothing ensembles and metabolic rates. The present sweat rate prediction model is more comprehensive than other existing models because it allows for prediction over a wider range of total heat load (metabolic heat production and heat exchange with the environment), and evaporative cooling capacity with greater applicability to different clothing systems. The present model predicts the sweat rate more accurately than the other existing models especially in extreme climatic conditions. The prediction of sweat rate using the formula in the present study instead of the nomograms used in two of the other models can be an added advantage of this model because of the wide usage of calculations and advanced state of computer technology.

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TABLE 1. Environmental conditions, exercise intensity, E_{req}, E_{max}, measured and predicted sweat rate (mean ± SE) in the first series of the present study, and comparisons with three other methods of prediction

Number of subjects	Clothing	Ta °C	rh %	Walking speed m·s⁻¹	Treadmill Grade %	E_{req} W·m⁻²	E_{max} W·m⁻²	$\dot{m}_{sw}$ g·m⁻²·h⁻¹		Predicted $\dot{m}_{sw}$, g·m⁻²·h⁻¹			
										Present study	Lustinec	Givoni	P4SR
8	shorts	40	32	rest	-	114 5	358 3	206 16	0.86 0.05	220	210	198	158
7	shorts	35	75	rest	-	66 5	168 1	164 16	0.62 0.04	179	150	113	92
7	fatigue	40	32	rest	-	100 4	286 2	217 14	0.70 0.03	213	180	173	204
8	fatigue	35	75	rest	·	61 4	133 1	198 15	0.47 0.02	184	120	105	132
8	shorts	40	32	1.34	0	228 4	409 3	401 15	0.86 0.02	414	340	392	421
8	shorts	35	75	1.34	0	169 5	193 2	386 23	0.67 0.04	431	370	289	450
8	fatigue	40	32	1.34	0	220 4	329 3	480 24	0.70 0.03	441	380	378	455
6	fatigue	35	75	1.34	0	185 5	158 1	580 31	0.49 0.04	517	400	314	550
8	shorts	40	32	1.34	5	244 3	427 3	465 19	0.80 0.03	434	400	420	395
8	shorts	35	75	1.34	5	197 5	202 2	556 43	0.55 0.04	493	400	336	560
8	fatigue	40	32	1.34	5	251 5	347 3	517 27	0.73 0.03	491	415	430	566
8	fatigue	35	75	1.34	5	201 6	163 1	691 41	0.44 0.02	654	480	341	660
4	shorts	49	20	1.34	0	302 10	408 6	507 51	0.91 0.07	549	470	518	580
7	fatigue	49	20	1.34	0	293 8	333 2	581 15	0.76 0.03	584	500	501	620
8	shorts	49	20	1.34	5	340 5	433 3	599 31	0.87 0.04	601	530	582	690

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TABLE 2. Environmental conditions, exercise intensity, E_{req}, E_{max}, measured and predicted sweat rate (mean ± SE) in the 2nd and 3rd series of the present study, and comparisons with three other methods of prediction

Number of subjects	Clothing	T_a °C	rh %	Walking speed m·s⁻¹	Treadmill Grade %	E_{req} W·m⁻²	E_{max} W·m⁻²	$\dot{m}_{sw}$ g·m⁻²·h⁻¹		Predicted $\dot{m}_{sw}$, g·m⁻²·h⁻¹			
										Present study	Lustinec	Givoni	P4SR
2nd Series													
8	fatigue	46	30	1.34	0	222 ± 2	325 ± 4	390 ± 19	0.85 ± 0.04	460	380	381	410
8	sweat suit	37	80	rest	-	78 ± 4	20 ± 1	556 ± 52	0.22 ± 0.02	558	*	125	210
7	sweat suit	37	80	1.34	0	206 ± 4	32 ± 1	932 ± 88	0.35 ± 0.04	1190	*	315	1100
5	fatigue & over-garment	37	80	1.34	0	197 ± 6	92 ± 2	849 ± 64	0.34 ± 0.02	714	*	328	1100
8	fatigue	37	80	1.34	0	192 ± 4	120 ± 2	767 ± 51	0.39 ± 0.03	617	500	323	1100
8	shorts	22	30	1.34	0	73 ± 6	448 ± 10	126 ± 15	0.93 ± 0.11	127	100	127	*
8	shorts	40	30	1.34	0	213 ± 5	234 ± 2	670 ± 45	0.49 ± 0.03	606	425	364	450
3rd Series													
10	shorts	49	20	1.34	0	297 ± 5	439 ± 6	502 ± 19	0.90 ± 0.03	522	460	510	605
10	shorts	54	10	1.34	0	362 ± 4	525 ± 7	586 ± 23	0.94 ± 0.03	586	530	621	710
10	shorts	37	80	1.34	0	188 ± 4	137 ± 3	560 ± 27	0.51 ± 0.02	561	500	318	1040
10	shorts	20	40	1.34	0	52 ± 4	439 ± 9	95 ± 13	0.91 ± 0.06	91	90	90	*
10	shorts	41	80	rest	-	106 ± 2	40 ± 2	584 ± 48	0.28 ± 0.02	560	*	175	790
10	shorts	35	90	1.34	0	173 ± 4	116 ± 3	554 ± 41	0.49 ± 0.04	556	500	292	1040
10	shorts	49	20	1.34	5	350 ± 7	405 ± 9	646 ± 32	0.82 ± 0.02	637	550	598	.724
10	shorts	49	20	1.34	0	309 ± 5	424 ± 7	516 ± 13	0.90 ± 0.02	551	480	530	.620

*out of the range of the model.

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TABLE 3. Comparison of the predicted sweat loss with the measured results of other investigators

| | experimental conditions | | | | | $\dot{m}_{sw}$, $g \cdot m^{-2} \cdot h^{-1}$ | |
	T_a °C	rh %	wind speed $m \cdot s^{-1}$	clothing	effort	measured	predicted
Royal Naval Tropical Research Unit (14)	32	80	1.6	shorts	climbing 12" bench 12 cycle·min⁻¹	186	178
	32	80	0.2	shorts	"	256	241
	32	80	1.6	shorts	rest	65	72
	32	80	0.2	shorts	rest	71	102
	32	80	0.2	overall	rest	99	115
	32	80	1.6	overall	rest	76	80
	32	80	1.6	overall	climbing 12" bench 12 cycle·min⁻¹	213	235
Givoni (7)	49	25	0.5	shorts	"	539	522
	35	23	2.0	shorts	rest	103	115
	36	88	2.0	shorts	rest	203	199
Candos et. al. (5)	48	33	$E_{req} = 260W$; $E_{max} = 260$ W			550	588
Nadel et. al. (16)	36	50	15 min work 720 kpm·min⁻¹ + 15 min rest			316	330
Gonzalez et. al. (11)	40	32	$E_{req} = 193$ W·m⁻² $E_{max} = 401$ W·m⁻²			170 (a)	230

a. Net evaporative sweat rate (weight loss, minus metabolic weight loss, respiratory water loss and dripped sweat).

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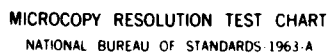
MICROCOPY RESOLUTION TEST CHART

NATIONAL BUREAU OF STANDARDS-1963-A

ACKNOWLEDGEMENT

FIGURE LEGENDS

Figure 1.   Relationship between $E_{req}/\dot{m}_{sw}$ and E_{max} derived from the first series (individual points).

Figure 2.   Relationship between $E_{req}/\dot{m}_{sw}$ and E_{max} for the three groups of the first series (each point is an average of the group for each condition).

Figure 3.   Relationship between measured and predicted sweat rate for the first series (individual points).

Figure 4.   Relationship between $E_{req}/\dot{m}_{sw}$ and E_{max} for all three series of experiments (each point is an average of a group in one condition).

Figure 5.   Comparison of four methods to predict the sweat rate observed in the present study. The solid line is the line of identity and the dashed lines present the $\pm$ 20% range from this line of identity.

Figure 1 - Prediction of Sweat Rate

$E_{req}/\dot{m}_{sw}$

$Y = 0.0530\ X^{0.452}$

$r = 0.87$

E_{max} $w \cdot m^{-2}$
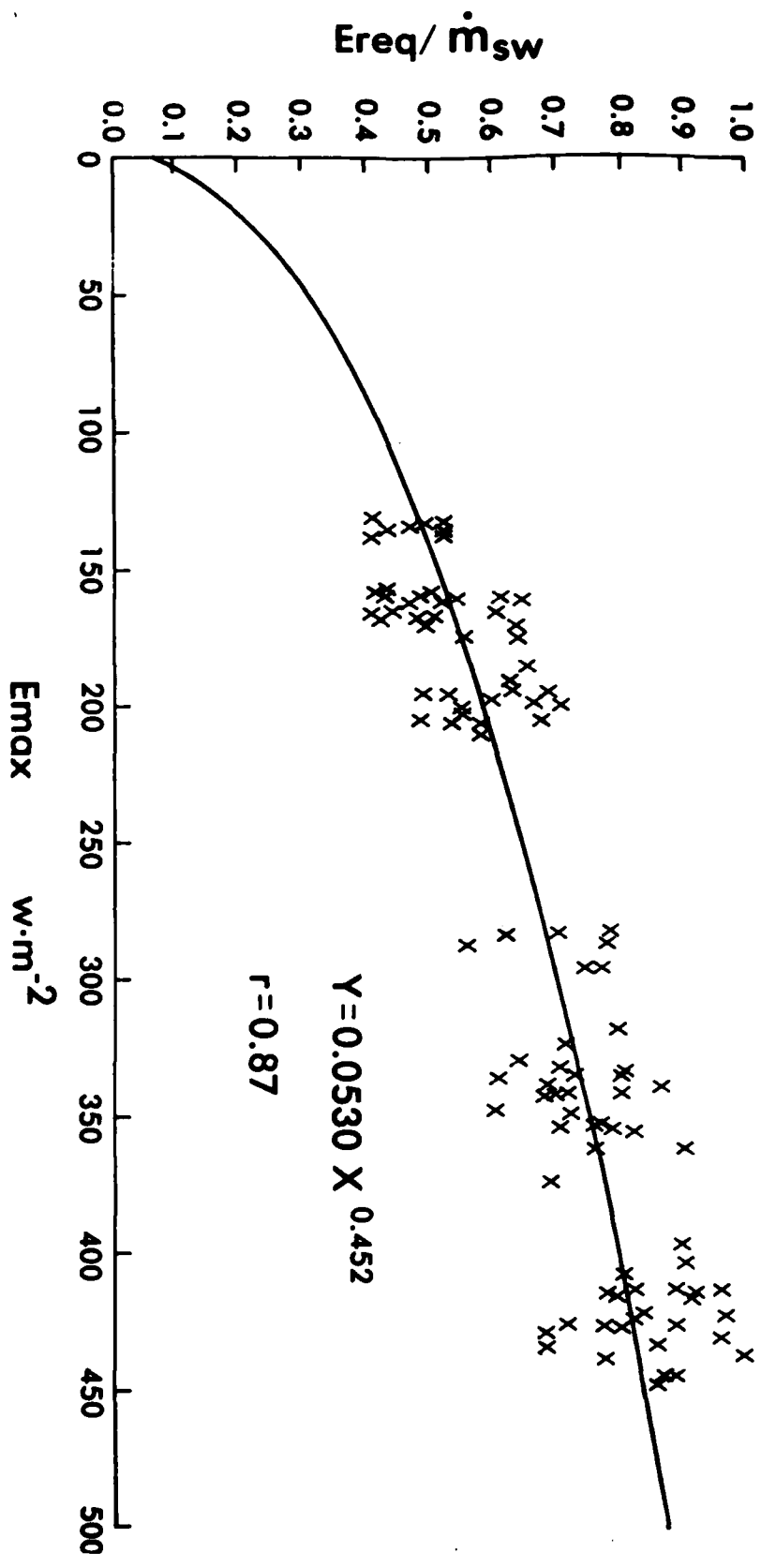
Figure 2 - Prediction of Sweat Rate

$Y = 0.0530 \ X^{0.452}$

O REST
△ LEVEL
× 5% GRADE

$E_{req}/\dot{m}_{sw}$

$E_{max} \ w \cdot m^{-2}$
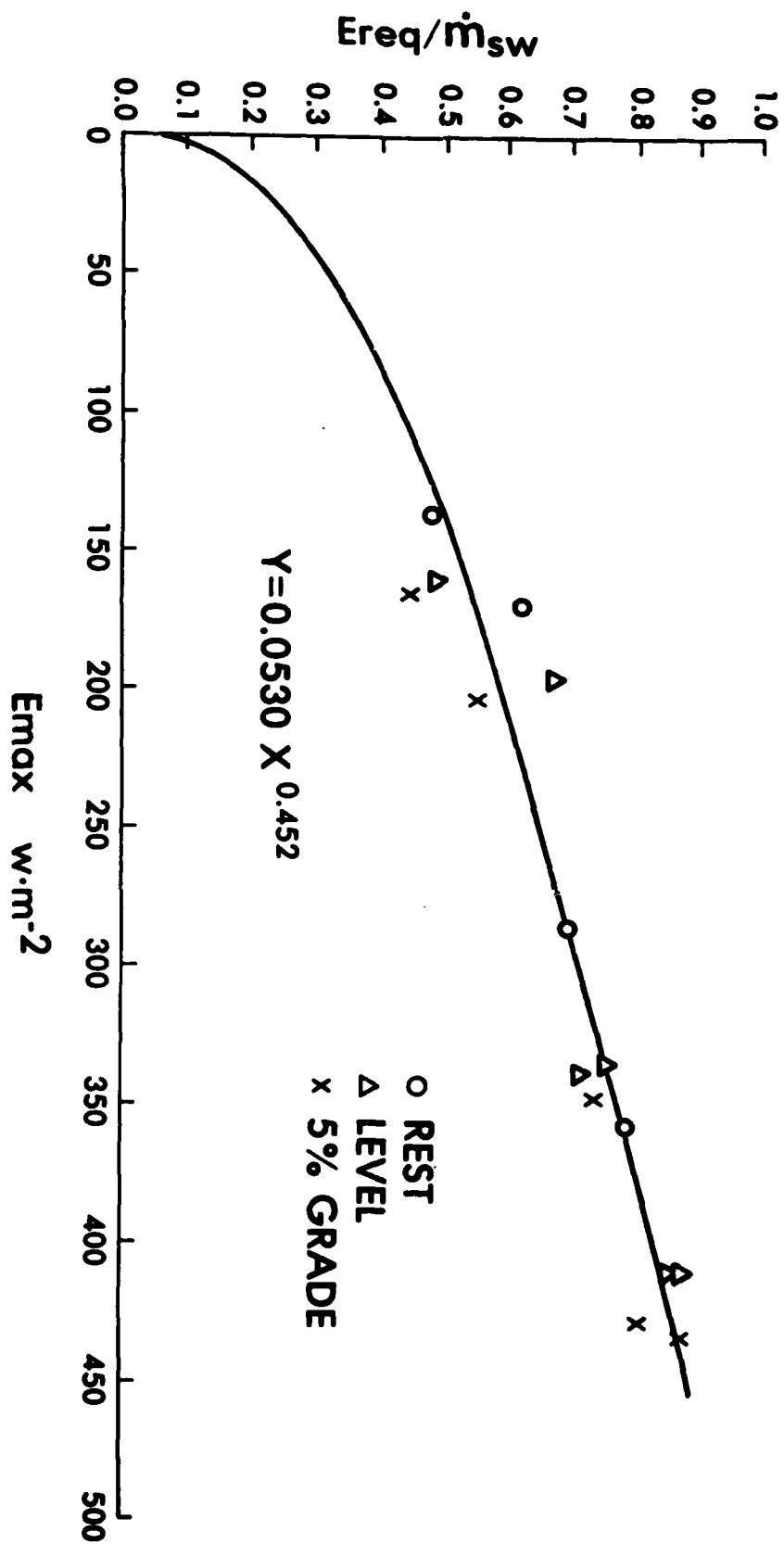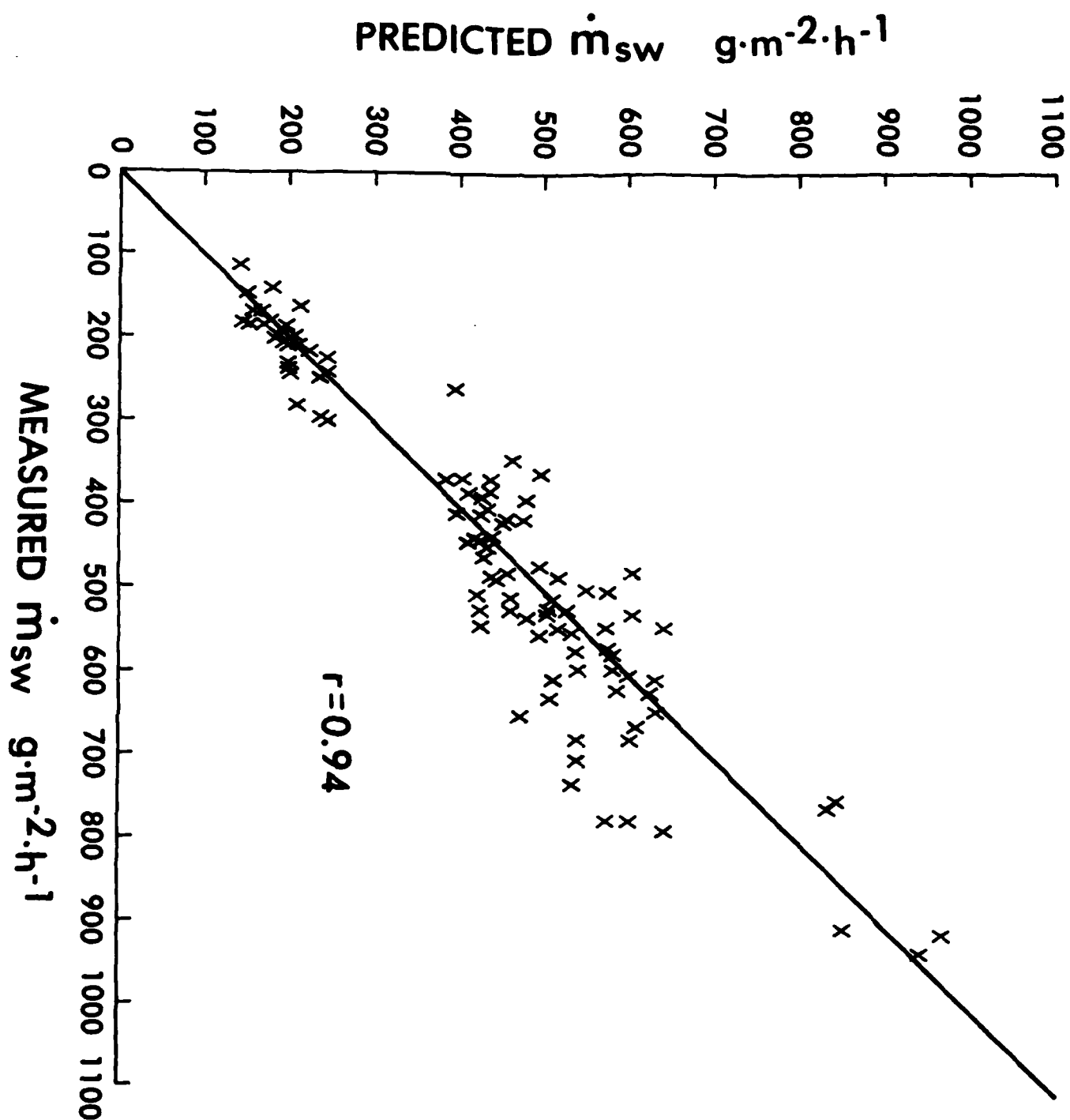
Figure 3 - Prediction of Sweat Rate

r=0.94

Figure 4 - Prediction of Sweat Rate

$Y = 0.0537 X^{0.455}$

× 1st SERIES
△ 2nd SERIES
○ 3rd SERIES

$E_{req}/\dot{m}_{SW}$

E_{max} $w \cdot m^{-2}$
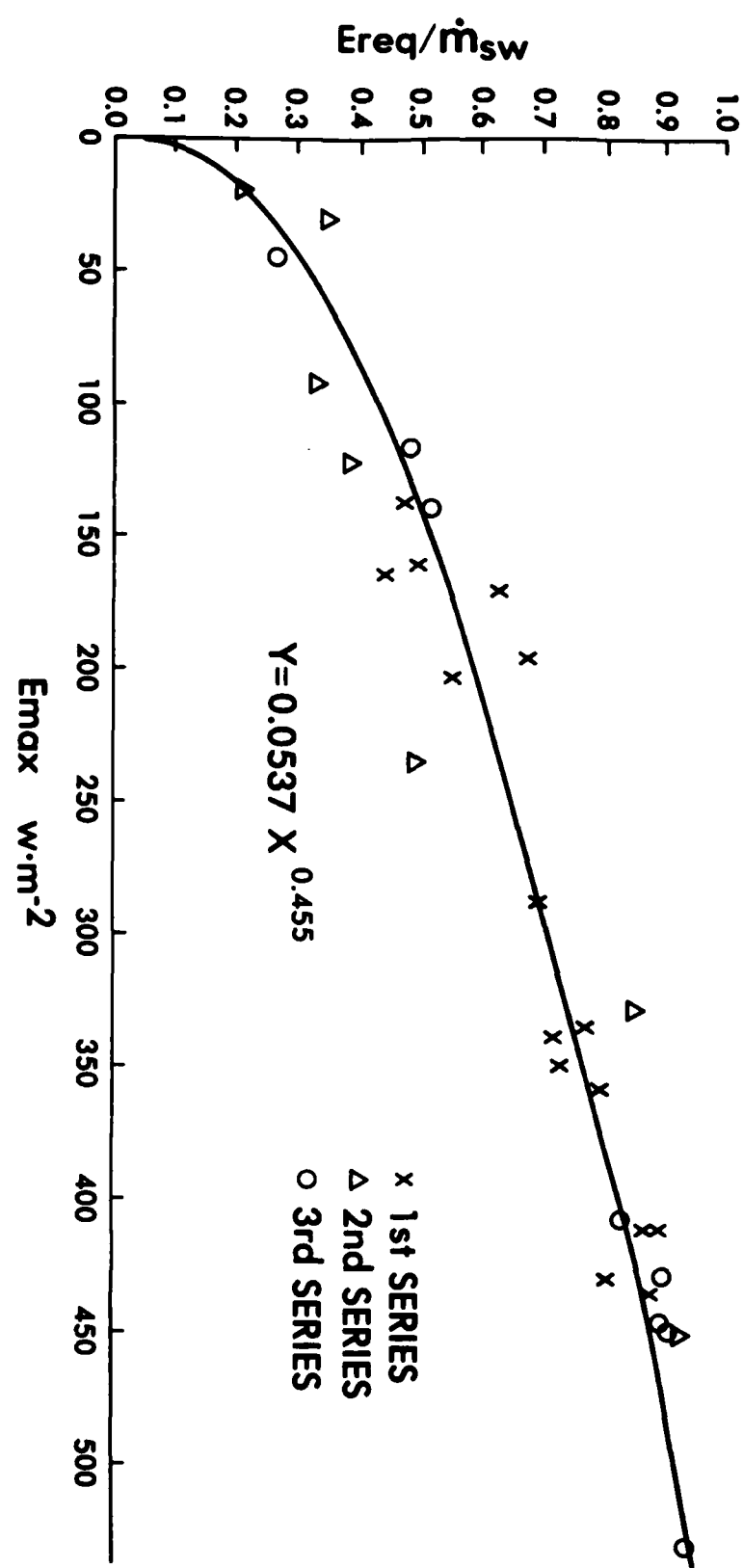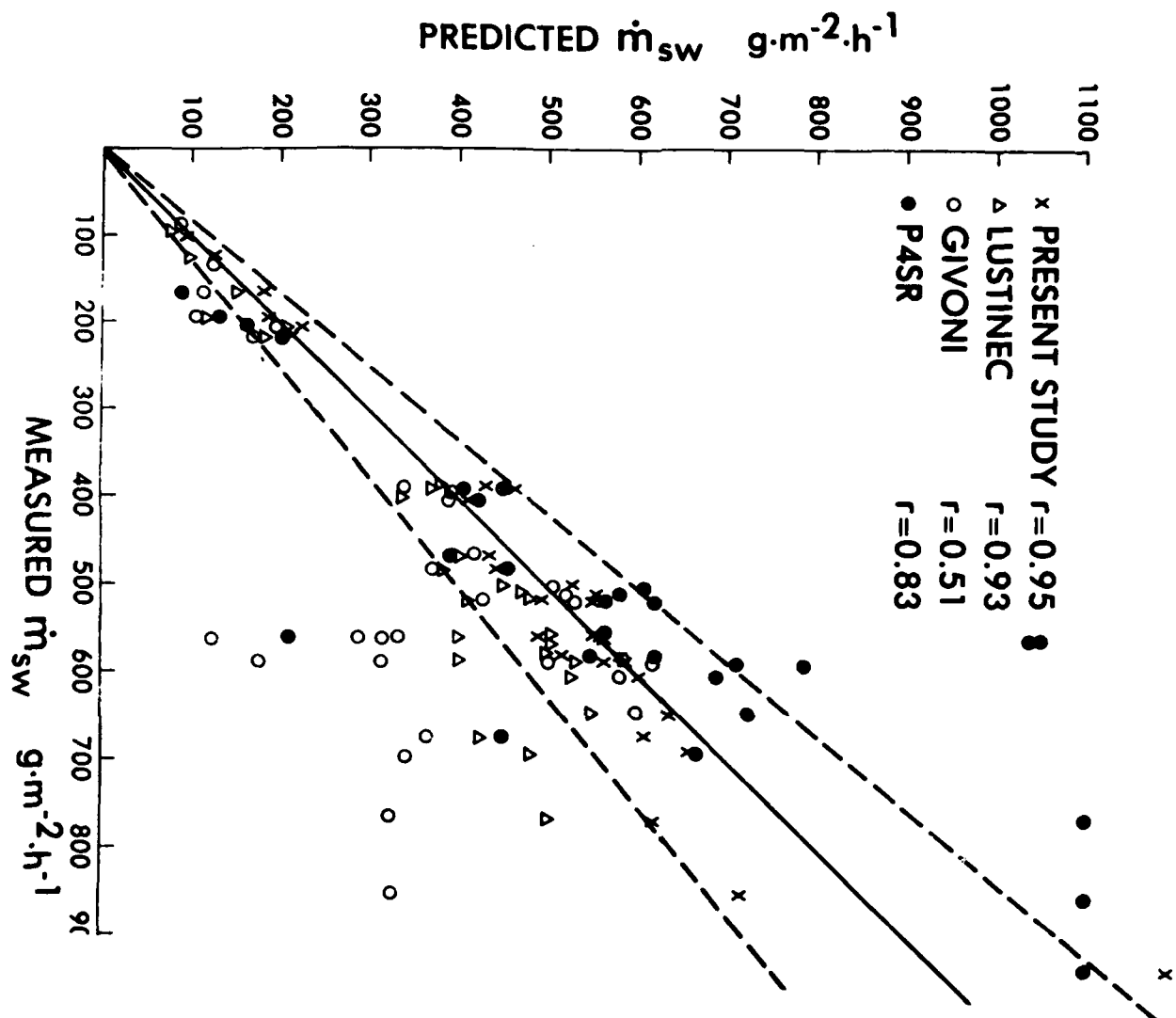
Figure 5 - Prediction of Sweat Rate

MODIFICATION OF THE MONARCH BICYCLE ERGOMETER

FOR UNDERWATER EXERCISE

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ABSTRACT

A standard Monarch bicycle ergometer was modified for underwater exercise by removal of the friction belt and attachment of one to six metal fins to the fly-wheel. Three fins could be fastened to either side of the flywheel. The fins used on the left side of the wheel were made of standard perforated angle iron with the perpendicular side measuring 38 mm; those on the right side were made from the same length of non-perforated angle iron but with a perpendicular side of only 26 mm. Net surface area of the two types of fins (excluding area of perforation) was the same. Oxygen uptake ($\dot{V}O_2$) was found to be: $\dot{V}O_2 = a(rpm)^b + 0.25$, $1 \cdot min^{-1}$ with $a = 0.00164 - 0.00104n + 0.000266n^2 - 0.00002n^3$; $b = 1.64 + 0.506n - 0.104n^2 + 0.00667n^3$, when n is the number of fins. The correlation coefficient (r) between measured and predicted $\dot{V}O_2$ was $r = 0.98$. The preferable range of pedaling speeds was 29-40 rpm to maintain a constant speed for up to an hour. Major advantages of this modified ergometer for underwater exercise are: 1) the modification is simple and the same ergometer can be used for land exercise, 2) the ergometer can be biologically calibrated and used for a wide range of exercise oxygen uptakes, and 3) subjects can perform for a proportionally longer time period than other modifications of the same ergometer.

Index terms: bicycle ergometry; oxygen uptake; pedaling rate; water immersion exercise.

INTRODUCTION

Early research evaluating man's physiological responses to exercise in water involved cumbersome and somewhat awkward techniques for measurement of exercise intensity while subjects were free swimming. Expired air collection bags were either towed by the swimming subject (12) or carried alongside the pool by an investigator (1, 6). These approaches were technically difficult from the standpoint of data collection and were limited in both the range and specificity of exercise intensities which could be achieved.

The use of a tethered swimming apparatus (8, 9) and the development of a swimming flume (2, 5) enabled researchers to specifically regulate exercise intensity and eliminated the problem of the moving subject. Since the use of both of these techniques required swimming skill, a basic problem for the physiologist still existed in that the research on immersed exercising subjects was limited to swimmers.

Craig and Dvorak (3) described an electrically braked arm-leg ergometer which could be used in water while the subject was immersed to the neck. This ergometer could be operated with minimal familiarization for the subject and could be used either in air or in water. This design yielded a very accurate measure of power output but required a variety of technical support to properly assemble. It would be difficult for most laboratories to duplicate such a design.

Previously, a standard Monarch bicycle ergometer was minimally modified and then used as an underwater ergometer (10). This modified ergometer could be used by anyone capable of pedaling a Monarch bicycle on land. Exercise intensities up to maximal limits could be achieved by increasing the pedaling frequency. It was found, however, that for long term, high intensity exercise, subjects could not maintain the high pedal frequencies required for moderate-to-heavy physical effort and frequently complained of discomfort.

Since the immersion of a modified Monarch bicycle ergometer appears to be a practical method for evaluation of underwater exercise, a system whereby exercise intensity can be progressively increased in a manner other than by dramatically increasing pedal frequency was deemed necessary. The purpose of this study was to describe a simple modification of the Monark bicycle ergometer applicable for graded exercise up to an individual's maximal aerobic capacity in which the pedaling frequency could be maintained constant for prolonged periods of time.

METHODS

The Ergometer

A modified Monarch bicycle ergometer was used for underwater exercise. The modifications made were: 1) removal of the friction belt, 2) fastening of a magnetic switch to the frame and a small magnet to the left pedal crank arm for recording revolutions on a digital counter, and 3) drilling of three 10 mm holes in the flywheel into which were attached up to six fins, as illustrated in Figure 1. Three fins could be fastened to either side of the flywheel. The fins that were used on the left side of the wheel were made from standard perforated angle iron with the perpendicular side measuring 38 mm (see Figure 2). Those on the right side (fin numbers 4, 5 and 6) were made from the same length of non-perforated angle iron but with a perpendicular side of only 26 mm. The net surface area of the two types of fins (excluding the area of perforation) was the same.

Subjects

Six male volunteers served as subjects. All subjects were totally informed with regard to experimental risk and gave their written informed consent. The physical characteristics of the subjects were: age, 25.8 ± 2.1 yr (20 - 35); weight, 83.2 ± 4.3 kg (69.6 - 100.0); and height, 178.1 ± 1.6 cm (172.2 - 183.0).

Procedure

The subjects, wearing bathing suits and mesh nylon pocketed vests which contained 11.5 kg of lead weight, were immersed up to neck height in 26 - 29°C water. They sat quietly on the ergometer seat for 10 min before a 2-min expired air sample was collected. After the resting samples were taken, the subjects operated the ergometer under various combinations of pedaling speeds and number of fins. The pedaling rate, given by a metronome, was increased by approximately 10 rpm each 12 min. Ten min of each exercise bout was used to reach a steady state and then the last two min were required for collection of an expired air sample. The pedaling frequency ranged from 15 to 63 rpm for free wheeling (no fins), from 20 to 60 rpm for one fin, from 20 to 50 rpm for two fins, from 20 to 45 rpm for three fins and from 20 to 40 rpm for four, five and six fins. Each subject was not exposed to all combinations. Two-min expired air samples were collected in Douglas bags, the volume was measured in a Collins spirometer and converted to standard environmental conditions (STPD), and the O_2 and CO_2 concentrations were measured with an Applied Electrochemistry Model S-3A O_2 analyzer and Beckman LB-2 infrared CO_2 analyzer. In addition, the subjects were asked to maintain a constant pedaling speed at an exercise intensity of 85% of their maximal oxygen uptake ($\dot{V}O_2$ max) for up to an hour at different combinations of number of fins and pedaling rates (30, 40, 50 and 60 rpm).

Statistical Treatment

The power curve fit of oxygen uptake ($\dot{V}O_2$) contrasted to rpm and number of fins ($y = ax^b$) was calculated as a linear regression of the logarithmic expression: $\ln y = \ln a + b \ln x$. In a similar way the exponential curve fit ($y = ae^{bx}$), the logarithmic curve fit ($y = a + b \ln x$), the parabolic curve fit ($y = a + bx + cx^2$), and $y = a + b/x$, $1/y = a + b/x$ and $y = a + b\sqrt{x}$ were all examined, as well as the associated linear regression and the polynomial regression.

RESULTS

After two months of using the modified Monarch bicycle ergometer for several hours each day, no major mechanical malfunctions of the cycle occurred except for a few breaks in the handlebar post, the seat post and the pedal cranks.

The subjects had difficulty maintaining a constant speed when the pedaling frequency was below 29 or above 40 rpm regardless of the number of fins. On the other hand, when the exercise intensity was less than 85% of the $\dot{V}O_2$ max, the subjects could adjust to a speed range of 29 to 40 rpm even if the riding time was a full hour.

The best fit between $\dot{V}O_2$ and pedaling speed was found to be:

$$\dot{V}O_2 = 0.250 + a(rpm)^b; 1 \cdot min^{-1}$$

For the individual number of fins the a values were found to be 0.00158, 0.00084, 0.00050, 0.00032, 0.00039, 0.00064 and 0.00060 for 0, 1, 2, 3, 4, 5 and 6 fins, respectively; and b values: 1.66, 2.04, 2.24, 2.46, 2.45, 2.33 and 2.39, respectively. Corresponding r values were 0.94, 0.93, 0.93, 0.96, 0.94, 0.99 and 0.95, respectively (see Figures 3 and 4). Analyzing all of the results combined yielded a general expression for the a and b coefficients for any number of fins as:

$$a = 0.00164 - 0.00104n + 0.000266n^2 - 0.00002n^3$$

$$b = 1.64 + 0.506n - 0.104n^2 + 0.00667n^3$$

where n is the number of fins, as illustrated in Figure 5. Figure 5 also shows that below 25 rpm the resolution among number of fins in terms of $\dot{V}O_2$ is minimal. Calculation of the predicted $\dot{V}O_2$ using the above equations plotted against the measured $\dot{V}O_2$ for all the measurements together (total 154 measures) yielded an r = 0.98, as shown in Figure 6.

DISCUSSION

The major problems of adapting a land bicycle ergometer for underwater usage involve the durability of the instrument, the calibration of the ergometer, the ability of the instrument to provide reasonable comfort for the subjects, and the ability of the subjects to pedal the bicycle underwater at a constant exercise intensity for a prolonged period of time at varying levels of oxygen uptake.

Starting with the simple concept of submerging a Monarch ergometer, the present study was undertaken to eliminate the problem of high pedaling frequencies needed to elicit high exercise intensities. In our modified ergometer, exercise intensities were progressively increased by increasing the drag produced on the rotating flywheel by the addition of fins rather than by increasing the resistance through high pedaling rates as was done by Morlock and Dressendorfer (10). In their modification, pedaling in a comfortable range of pedaling speeds (29 - 40 rpm) elicited an oxygen uptake of $1/2 - 3/4$ $1 \cdot min^{-1}$, while to reach a $\dot{V}O_2$ of 4.0 $1 \cdot min^{-1}$ their subjects had to pedal at about 80 rpm. In the present modification, such a $\dot{V}O_2$ (~ 4.0 $1 \cdot min^{-1}$) could be achieved by using 4 fins with a pedaling rate of only 40 rpm which is still within the preferred pedaling range for underwater exercise. Thus, the present modification has an advantage over the previous one, in that exercise intensity can be increased without substantially increasing the pedaling rate. On land, one can pedal at a constant speed up to a rate of 80 rpm for prolonged periods (4, 7, 11). Individuals subjectively and physiologically prefer high pedaling rates ($\sim$80 rpm) on land (7, 11). However, when underwater, as was shown in this study, it is very difficult to pedal at constant rates above 40 rpm because of the water resistance to body movements. By varying the number of fins from 0 to 4 with pedal frequencies of 30 to 40 rpm, a range of $\dot{V}O_2$ between 0.5 and 4.0 $1 \cdot min^{-1}$ could

be achieved. In this way, one could grade the exercise intensity up to a maximal level at a comfortable and easily maintained pedaling rate. It is not recommended to use more than 5 fins attached to the flywheel because as seen in Figure 5, the oxygen uptake curves for 5 and 6 fins are very close without much discrimination.

The modifications made on the Monarch bicycle ergometer were minimal and did not alter its suitability as a standard bicycle ergometer on land. It takes very little time to convert between the land and the underwater modes. Even long term usage of this modified Monarch bicycle for underwater exercise does not result in severe mechanical malfunction. The few breaks in the handlebars, seat posts, and in a pedal crank that were observed in this study were attributable to high intensities of exercise rather than to underwater usage, per se. Periodic greasing and painting can prevent any rusting of either the moving or the static parts of the ergometer. According to our experience with this modification, it is important to decrease the subject's buoyancy by using a weight belt or vest to help keep his body on the seat. Another means to keep the subject on the ergometer seat is to strap him to the seat by using a seat belt.

The only method of calibrating the present modified Monarch bicycle ergometer is through a biological calibration as conducted in the present study. The external mechanical work cannot be calculated in the same manner as for the land ergometers.

In conclusion, the present modification of the Monarch bicycle ergometer for underwater exercise by using drag fins is simple and can be done in any laboratory. The modification does not prevent the continued use of the same ergometer for land work. The modified ergometer can be biologically calibrated and can be used for a wide range of oxygen uptakes (rest to maximal aerobic power). Subjects can ride this modified ergometer for a proportionally long period of time at a constant pedaling speed with measurable comfort.

ACKNOWLEDGEMENT

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FIGURE LEGENDS

Figure 1. A photograph of a modified Monarch bicycle ergometer, showing the flywheel with three fins attached.

Figure 2. A technical drawing of the fin and the attachment of the fin to the flywheel.

Figure 3. Measured oxygen uptake ($\dot{V}O_2$) versus pedaling rate (rpm) for no fins, 1, 3 and 5 fins; the numbers beside the lines are the number of fins.

Figure 4. Measured oxygen uptake ($\dot{V}O_2$) versus pedaling rate (rpm) for 2, 4 and 6 fins; the numbers beside the lines are the number of fins.

Figure 5. Oxygen uptake versus pedaling rate for all 7 variations (0 - 6 fins) using the general equation: $\dot{V}O_2 = a(rpm)^b + 0.25; 1 \cdot min^{-1}$ and the general expressions for a and b (see text). The numbers beside the lines are the number of fins.

Figure 6. The relationship between measured and predicted oxygen uptake ($\dot{V}O_2$) using the general equation for any number of fins. The solid line is the line of identity.
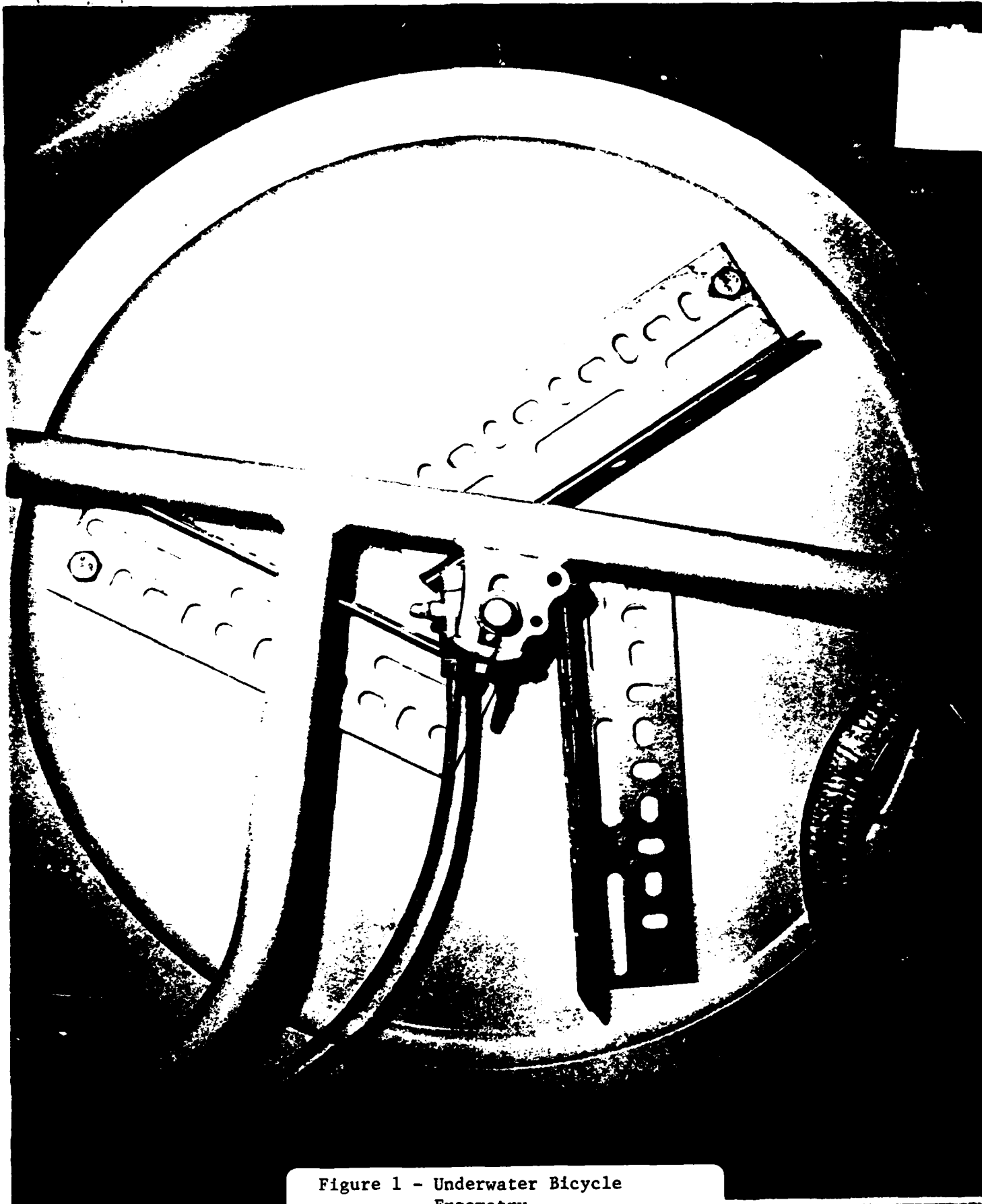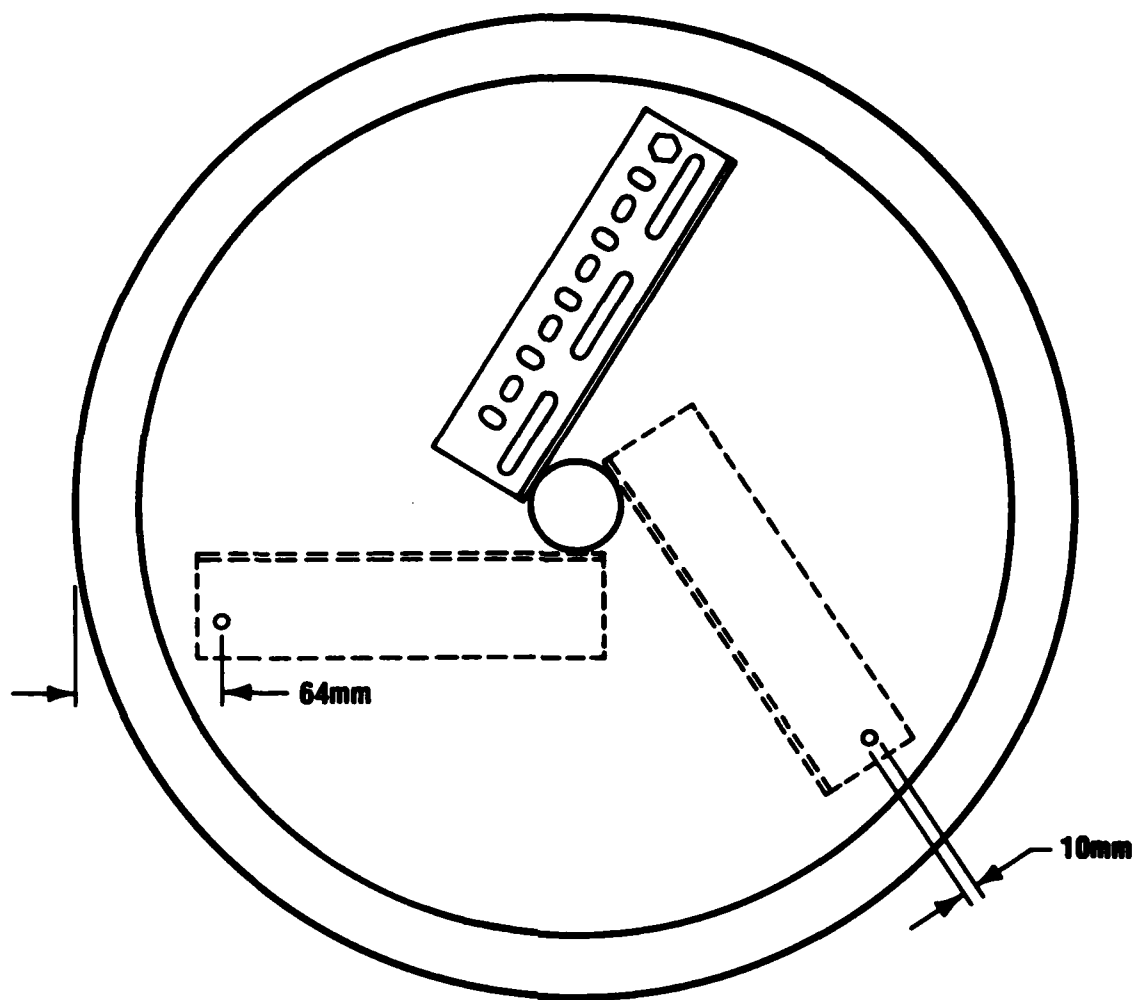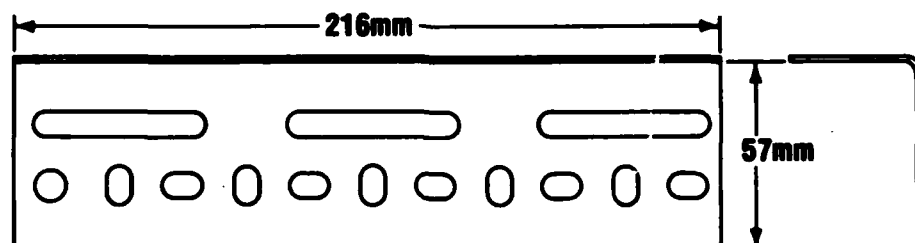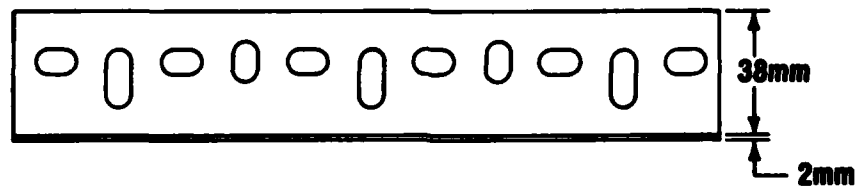
Figure 1 - Underwater Bicycle
Ergometry

PERPENDICULAR SIDE

ATTACHED SIDE　　　　　　　　　　　**END VIEW**
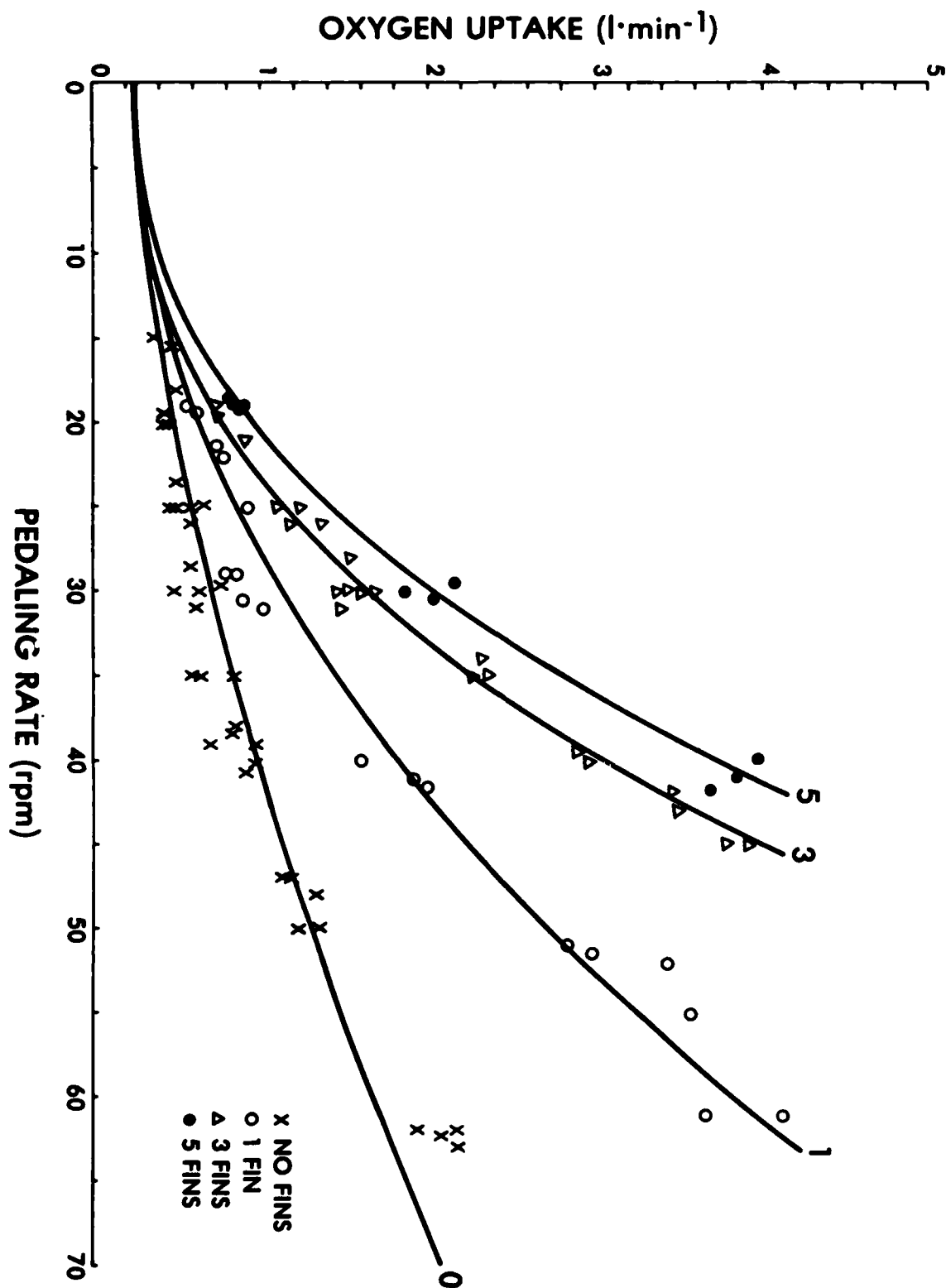
Figure 2 – Underwater Bicycle
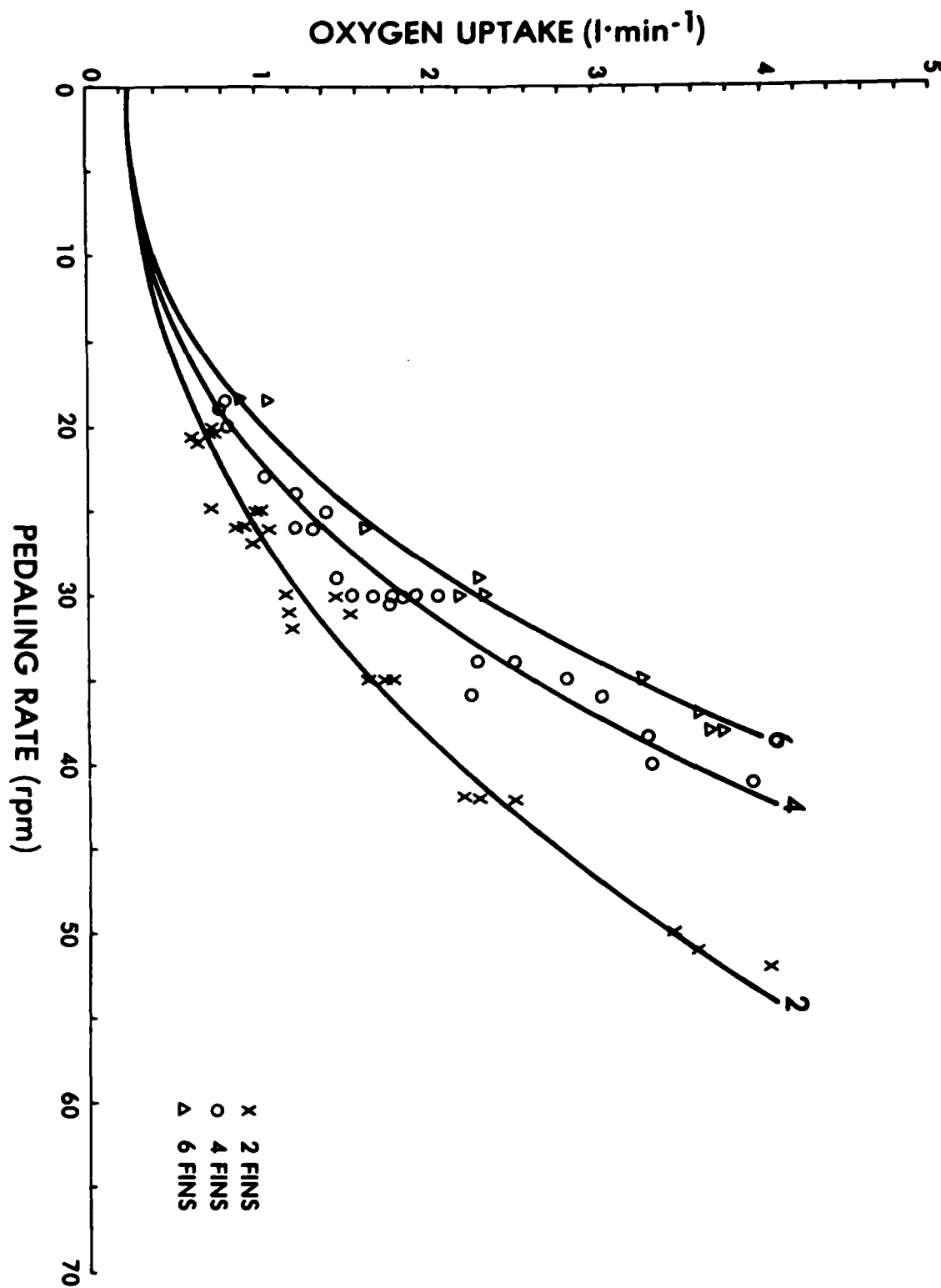Ergometry

Figure 3 – Underwater Bicycle
Ergometry
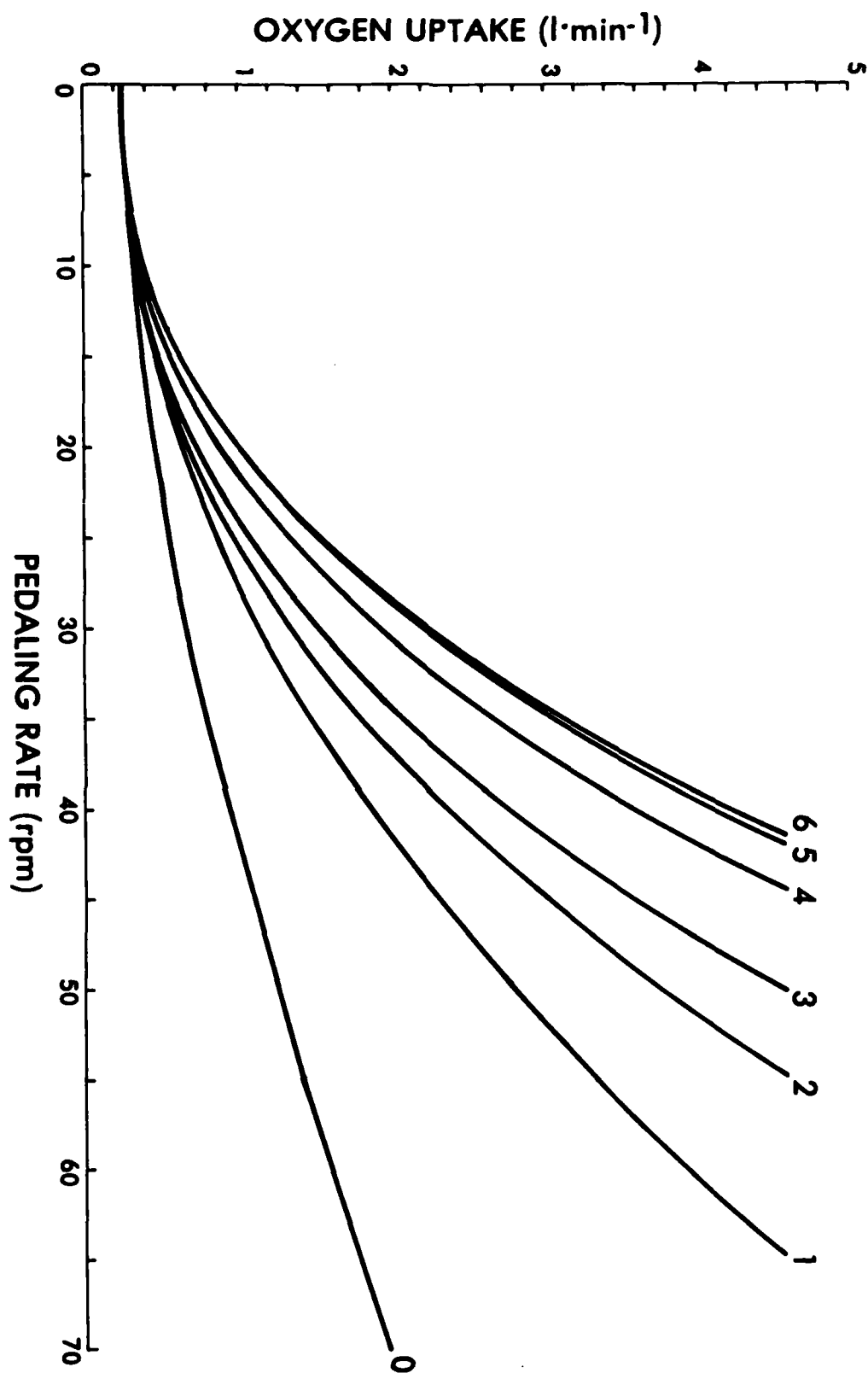
Figure 4 – Underwater Bicycle
Ergometry

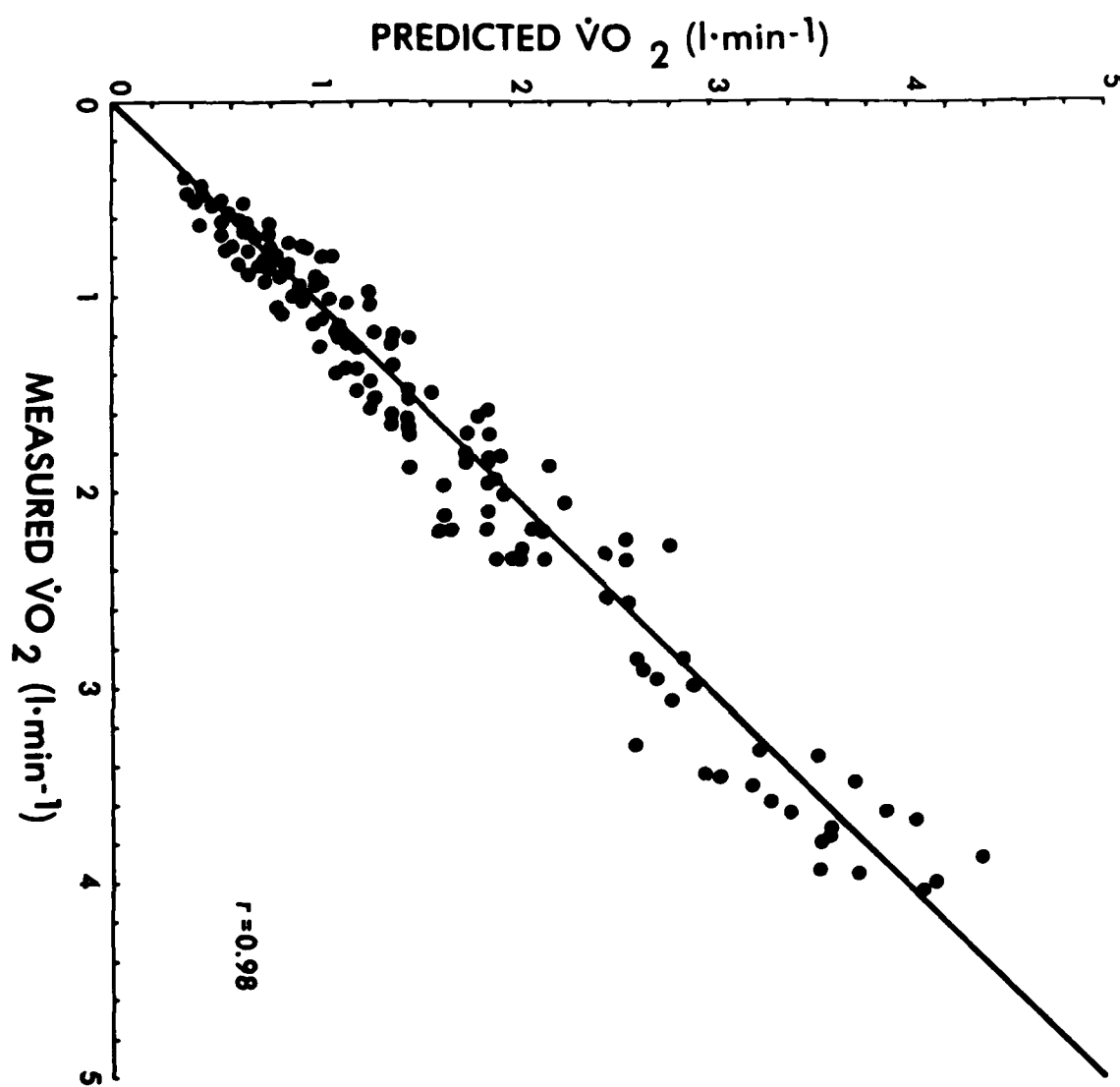Figure 5 – Underwater Bicycle
Ergometry

Figure 6 – Underwater Bicycle
Ergometry

PHYSIOLOGICAL AND HEMATOLOGICAL RESPONSES TO SUMMER

AND WINTER DRY-HEAT ACCLIMATION

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Running Head: Summer and winter acclimation to dry heat

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ABSTRACT

Differences between acclimation to heat at the end of winter (W) and at the end of summer (S) were studied on the same 8 male volunteers. Subjects were exposed to 40°C, 30% rh for 10 days on two separate occasions approximately 5 months apart (S and W). Daily exposures lasted 120 min: 10 min rest, 50 min walking 1.34 m $\cdot$ s^{-1} on the level, 10 min rest, 50 min walking. During W acclimation, rectal temperature (T_{re}) and heart rate (HR) decreased, sweat rate ($\dot{m}_{sw}$) remained unchanged, and plasma and red cell volume of the blood expanded. During S acclimation, HR decreased while T_{re} and $\dot{m}_{sw}$ remained unchanged, and plasma volume increased. The T_{re} of the acclimated subjects remained higher in W and $\dot{m}_{sw}$ lower than in S. It was concluded that acclimation does not totally eliminate the seasonal differences in thermoregulatory set-point and sweat sensitivity. Further, acclimation to a more severe heat did not improve the thermoregulatory set-point that was achieved by natural acclimatization to a milder heat, but affected the cardiovascular adjustment and caused greater plasma volume expansion. W acclimation caused both plasma and blood cell volume expansion while S acclimation affected only plasma volume.

Index terms: acclimatization; blood volume; plasma volume; seasonal acclimation differences; rectal temperature; heart rate; sweat rate; plasma protein; plasma osmolality; hematocrit; mean corpuscular hemoglobin concentration; hemodilution; thermoregulatory set-point; sweat sensitivity.

INTRODUCTION

Acclimatization is defined as: "a physiological change occurring within the lifetime of an organism which reduces the strain caused by stressful changes in the natural climate", while acclimation is defined as: "a physiological change occurring within the lifetime of an organism, which reduces the strain caused by experimentally induced stressful changes in particular climatic factors" (3). As one can see, the difference between the two definitions involves whether the changes are induced by natural or artificial climatic stimuli. In both acclimation and acclimatization, the major physiological changes are: a heightened sweating response, lowered heart rate and lowered internal body temperature during exercise in the heat (17, 19, 27, 28). Both acclimatization and acclimation therefore reduce the risk of heat injury (15). The main physiological mechanism of these two processes is an enhanced sweating responsiveness, via both peripheral and central pathways (17).

In addition to the classical physiological indices of acclimatization and acclimation as mentioned above, several recent studies have shown dynamic changes occurring in body fluid distribution with heat acclimation. Foremost of these changes is a rapid expansion of the plasma volume found to occur in the early days of heat acclimation (2, 25, 28). In that an expansion of the plasma volume is also typical with exercise, this hemodilution is found to be more enhanced and stabilized during acclimation induced by exercise in the heat (4, 20, 22, 24, 25). Several hypotheses exist as to the physiological mechanism(s) responsible for this hemodilution during acclimation. Senay attributes the expansion of the plasma volume to an influx of protein into the vascular volume (20), although others attribute it to an electrolyte shift (12). It has also

been shown that if dehydration is allowed to occur during exercise in the heat, this expansion of the plasma volume would not occur (7), unless the subjects were rehydrated following the exposure (6). Senay has also noted that a lack of plasma volume expansion is related to heat intolerance (23). Although the mechanisms involved remain speculative, it appears that an expansion of the plasma volume is a crucial hemodynamic change associated with cardiovascular adjustment to heat.

There are very few studies comparing the natural acclimatization and the artificial acclimation processes, with the majority of these studies suggesting that natural acclimatization is preferred over the artificial process (11, 13, 14, 31). Wyndham et al. (31), however, have made the assumption that during artificial acclimation, a higher level of adaptation to heat can be achieved than during natural acclimatization. All the above studies have dealt with different groups for the acclimation and the acclimatization experiments, and moreover, the acclimation usually took place in one country and the acclimatization in a foreign country. None of the above studies describe or compare the hemo-dynamic changes induced by acclimation in different seasons when the subjects are non-acclimatized (winter) or partially acclimatized (summer).

The purpose of this study was to compare both the physiological and hemodynamic acclimation responses of the same subjects to the same hot-dry environment, once in a state of the lowest natural acclimatization (end of the winter), and once in the highest state of natural acclimatization (end of the summer).

METHODS

Subjects

Eight male soldiers served as volunteer subjects. All subjects were totally informed with regard to experimental risk and gave their written informed consent. The physical characteristics of the subjects (mean $\pm$ SE) were: age, 22.5 $\pm$ 2.0 yr; height, 175.4 $\pm$ 2.9 cm; weight, 68.6 $\pm$ 2.8 kg; body surface area, 1.83 $\pm$ 0.05 m^2; and percentage of body fat, 17.0 $\pm$ 1.6%.

Procedures

The first phase of the study, the end of the summer acclimation (S), was conducted early in September and the second phase, the end of the winter acclimation (W), was conducted during the end of February and the beginning of March of the following year. The same subjects were used for both phases of the study. Prior to the heat exposures, all subjects underwent medical examination to determine their fitness for the study. The subjects, dressed in T-shirts, shorts, socks and indoor shoes, were concurrently acclimated for 10 consecutive days (A_1 - A_{10}) during both phases (S and W) by walking on a level motor-driven treadmill at 1.34 m $\cdot$ s^{-1} for two 50-min periods with a preceding and intervening 10-min rest period, at 40°C, 30% rh, 1 m $\cdot$ s^{-1} wind speed. A day before and a day after this acclimation period, the subjects were exposed to a comfortable environment of 20°C, 50% rh (control days C_1 & C_2) at the same treadmill walking speed and wind velocity.

During all heat exposures, rectal temperture (T_{re}) was recorded from a Y.S.I. rectal thermistor probe inserted ~ 10 cm beyond the anal sphincter. Skin temperatures were monitored with a three-point thermocouple skin harness (chest, calf and forearm) and mean weighted skin temperature (T_{sk}) was

calculated according to Burton (5). Using a Hewlett Packard 9825A Calculator and 9862A Plotter on-line during experimentation, both $\bar{T}_{sk}$ and T_{re} were plotted for each subject at approximately 2-min intervals. Heart rate was measured by radial artery palpation during the rest periods and after each 25 min of walking. Ad lib drinking was encouraged. At the end of the first rest period and at the end of each walking period, two-min expired air samples were collected in Douglas bags. The volume was measured in a Collins Spirometer and converted to standard enviromental conditions (STPD), and the O_2 and CO_2 concentrations were measured with an Applied Electrochemistry Model S-3A O_2 analyzer and Beckman LB-2 infrared CO_2 analyzer. A time weighted average metabolic rate (M) was calculated as 0.17 of the resting value plus 0.83 of the mean of the two level walking values. Total body weight losses were determined from pre- and post-walk measurements on a K-120 Sauter precision electronic balance (accuracy of ± 10 g) for calculation of sweat rate. Sweat rate ($\dot{m}_{sw}$) was determined from weight loss, adjusted for water intake, urine output, and respiratory and metabolic weight losses. The metabolic weight loss ($\dot{m}_r$) and the respiratory water loss ($\dot{m}_e$) were calculated according to Mitchell et al. (16) as: $\dot{m}_r = 0.53 \ \dot{V}O_2$ in $g \cdot min^{-1}$ and $\dot{m}_e = 0.019 \ \dot{V}O_2 \ (44 - P_a)$ in $g \cdot min^{-1}$, where P_a is the ambient water vapor pressure (mm Hg) and $\dot{V}O_2$ is the O_2 consumption $(1 \cdot min^{-1})$. The net sweat rate was normalized per m^2 surface area.

Criteria for terminating any heat exposure were a heart rate of 180 $b \cdot min^{-1}$ during exercise or 140 $b \cdot min^{-1}$ during rest, and/or a T_{re} above 39.5°C, dizziness, nausea, or dry skin.

Blood Analysis

Venous blood samples were drawn from each subject during both control days and on the 1st, 2nd, 3rd, 4th, 6th, 8th and 10th days of acclimation. Two

samples were taken on these days: one several min before entering the climatic chamber (pre-exposure), and the other between min 100 and 110 of exposure (post-exposure). The pre-exposure sample was taken after 20 min of resting in the erect position and the post-exposure sample was taken within one min of stepping off the treadmill. All blood samples were taken without stasis, using pre-heparinized Vacutainers.

The blood samples were analyzed for: hematocrit (HCT) in triplicate by the microhematocrit method (reported uncorrected); hemoglobin (Hb) in duplicate by the cyanmethemoglobin method; total protein (TP) in duplicate by an American Optical Refractometer; albumin (ALB) by the bromcresol green method (10), using a Gilford Automated 3400 spectrophotometer; and osmolality by a Precision System automatic osmometer. Plasma volume changes were calculated using the Dill and Costill method (9).

Assuming that the total amount of hemoglobin remained constant during each period of the study, changes in blood volume were calculated on each acclimation day when blood was drawn from the changes in hemoglobin concentration as:

$$\Delta BV_{c-x} (\%) = 100(Hb_c - Hb_x)/Hb_c, \text{ where}$$

Hb_c represents the pre-exposure hemoglobin concentration of the first acclimation day (A_1), Hb_x the hemoglobin concentration of the measured day, and ΔBV_{c-x} the blood volume change between the pre-exposure value of the first acclimation day and the particular measured day. Changes in the volume of the cellular phase of the blood were calculated by multiplying the blood volume changes for the measured day by the hematocrit. Another method (28) of estimating the changes occurring in the volume of the cellular phase of the blood was employed by calculating the mean corpuscular hemoglobin concentration (MCHC).

Statistical Treatment

Most variables were evaluated by use of a mixed design of several factors, with one factor being the two phases (summer and winter), the second being the day of the acclimation, and the third the time of the day (pre- and post-exposure). If a significant F-value was found ($P < 0.05$), critical differences were analyzed by Tukey's procedure to locate the significant mean differences.

RESULTS

Physiological Parameters

The metabolic rate varied between 164 and 174 $W \cdot m^{-2}$ throughout both phases of the acclimation without any significant differences between the summer and winter experiments, or between the days of acclimation of each season.

The rectal temperature (T_{re}) remained unchanged through the 10 days of acclimation at the end of summer, whereas during the winter acclimation, a moderate decrease in T_{re} was observed (average of $0.22^{o}C$). However, this difference was not significant. On the other hand, the winter T_{re} was consistently and signficantly ($P < 0.01$) higher ($0.15 - 0.35^{o}C$) than that which was found during the summer experiments (see Fig. 1 and Table 1). The changes observed in the mean weighted skin temperature (T_{sk}) were similar between the two phases, with a significant decrease ($P < 0.05$) in T_{sk} found between the first and the last days of acclimation in both phases (see Table 1). Heart rate (HR) significantly decreased ($P < 0.05$) from the first to the sixth day of acclimation, both in S (15.3 $b \cdot min^{-1}$) and W (18.2 $b \cdot min^{-1}$). During the later days of the acclimation, HR remained unchanged (Fig. 1, Table 1). Between the seasons, a

significant difference in HR was found only on the first day of acclimation (9.2 b·min^{-1} higher in W). Sweat rate ($\dot{m}_{sw}$) remained unchanged during acclimation in both phases. However, the summer $\dot{m}_{sw}$ was significantly higher (5-14%) than the winter $\dot{m}_{sw}$ during each day of exposure to heat (see Fig. 1, Table 1). No significant differences were found in any of the above parameters between the two control days.

During the summer experiments, the subjects' mean weight varied between 68.2 ± 3.2 kg (values that were observed on C_1, A_1, A_2 and C_2) and 69.1 ± 3.2 kg (on the sixth day of acclimation). During the winter exposures the ... an body weight ranged between 69.8 ± 3.3 kg (on C_1) and 70.5 ± 3.5 kg (on A_6).

The level of dehydration during the summer exposures (difference between initial and final weight) varied between 0.2% (on A_2) and 0.8% (on A_6) of the total body weight. During the winter experiment, the values ranged between 0.0% (on A_9) and 0.8% (on A_8).

Hematological Parameters

The initial values (pre-exposure values for the 1st control day) of hemoglobin (Hb), albumin (ALB), total protein (TP) and MCHC were similar for both phases ($P > 0.05$). However, the hematocrit (HCT) was found to be significantly lower ($P < 0.05$) for W, although the absolute difference (0.7%) was very small (see Table 2).

The hemoglobin (see Fig. 2, Table 2) showed a similar pattern in both phases (W and S), as it decreased significantly ($P < 0.05$) to its minimal value on the sixth day of acclimation, and then increased significantly ($P < 0.05$) by A_{10}. The winter values for hemoglobin were lower, but not significantly lower ($P > 0.05$) as compared to the summer values. In both acclimation phases, the daily pre-exposure levels of Hb were significantly higher ($P < 0.05$) than at the end of the exposure, indicative of hemodilution.

The hematocrit (see Table 2) showed a similar pattern to that of Hb during the summer exposures (decreasing in the first half of the acclimation period and then increasing). However, in the winter exposures the changes were not significant. In both phases of these experiments, the pre-exposure values were significantly higher than the post-exposure values (indicating plasma volume expansion). While the summer hematocrit values for the first and last days of acclimation were significantly higher in comparison to the winter, no significant difference was found on A_6 between S and W (see Table 2).

The MCHC, which is a combination of the two previous parameters (Hb and HCT) showed a pattern consistent with a hemodilution process: significantly higher post-exposure than pre-exposure values; significantly lower values on A_6 for both S and W; significantly higher S values than W at the middle of the acclimation period, but significantly higher W than S values at the beginning and at the end of the acclimation (Fig. 3, Table 2).

In each season, the highest blood volume value was found on the sixth day of acclimation, and the lowest on the first day. No significant differences were found between S and W values for this parameter. In both seasons the post-exposure values were significantly higher than the pre-exposure values, representing a 1.1 - 2.8% blood volume expansion during exercise (see Figure 4).

A similar pattern was observed in the cellular phase of the blood (Figure 4), except that the winter values for the first and the last days of acclimation were significantly lower than the summer values (44.4 vs 47.2% for the first day and 47.6 vs 49.3% for the last day). No significant difference was found during the sixth day (48.7% for the summer and 49.5% for the winter) of acclimation.

The differences (post-exposure minus pre-exposure) in plasma volume values (Δ PV) calculated daily using Dill and Costill's method showed 5.7 - 6.7%

plasma volume expansion during the summer exposures and 2.2 - 6.2% expansion during the winter experiments (see Figure 5, Table 2); all of these differences were found to be significant ($P < 0.05$). Throughout the seasonal acclimation, no significant differences were found between days during the winter, whereas in the summer, A_6 values were significantly higher than A_1 or A_{10} values for both pre- and post-exposures. Between seasons, the only significant differences were found on A_6 (summer values higher than winter values, $P < 0.05$).

During both summer and winter exposures, the albumin (ALB) concentration was found to be significantly lower at the end of the daily exposure as compared to the pre-exposure values (Fig. 6, Table 2). During the summer acclimation, a significantly lower ALB concentration was found during the middle of the acclimation period (A_6), in comparison to the beginning or the end of the acclimation period. During the winter, such differences could not be shown. The only seasonally significant difference was found on A_6 (S lower than W).

Analyzing the total protein (TP) blood levels (see Fig. 7) yielded significant changes within both phases, but no differences between the two seasons. Significantly lower ($P < 0.05$) values were found in the middle of each period (A_6), as compared to A_1 or A_{10}. As with ALB concentration, lower values were recorded daily for post-exposure as compared to the pre-exposure values.

The osmolality values ranged between 268 ± 3 (summer, A_6 post-exposure) and 290 ± 2 mOsm $\cdot l^{-1}$ (summer, A_1 pre-exposure). No significant differences were found either between seasons or between pre- and post-exposure values. In the summer experiments the values for the first day of acclimation (A_1) were found to be higher than A_6 or A_{10} (see Table 2).

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DISCUSSION

Since the same test subjects served in both S and W phases and spent the whole year encompassed by the study in the same environment while performing similar activities, these subjects can be considered a homogeneous test group. The experiments were conducted in the northeast region of the USA, with its typical cold winter (below freezing temperatures) and warm summer (daily maximum ambient temperature of $30 - 32^{\circ}C$). One therefore could have expected that the subjects would be unacclimated to heat during the winter experiments and at least partially acclimatized during the summer exposures. Analyzing the T_{re} results supports this assumption. The T_{re} remained unchanged during the summer exposures, giving an indication that in terms of internal thermoregulatory set-point, the acclimatization procedure had already been completed naturally. However, during the winter experiments, the drop in T_{re} indicates that the acclimation had to be achieved artificially.

The significant difference in T_{re} between summer and winter phases that remained even after 10 days of acclimation suggests a different thermo-regulatory set-point for the different seasons. This difference in set-point cannot be totally eliminated by acclimation. Consequently, it is almost impossible not to compare this difference to the differences in T_{re} during the circadian rhythm (1). The seasonal differences in T_{re} parallel the differences in sweat rate, where the summer sweat rate was consistently and significantly higher than in the winter, regardless of the stage of acclimation. The higher T_{re} in the winter, combined with the lower sweat rate in comparison to the summer, suggests a lower sweat sensitivity in the winter than in the summer (26), both before and after acclimation.

The HR on the other hand showed a different manifestation: it dropped significantly both during the winter and during the summer experiments, suggesting that in terms of cardiovascular adjustment, the subjects were not fully acclimatized either in the winter or in the summer. Obviously, the changes in HR were of a greater magnitude during the winter because of a lower natural stage of acclimatization. At the end of the acclimation, the subjects showed similar (P > 0.05) HR for both phases (W and S), which is an indication of reaching a similar state of cardiovascular adjustment. In both seasons, these findings are in agreement with those of Wyndham et al. (29). In their study, the investigators defined days two and three in the heat as phase two of acclimation. These authors attributed the decrease in HR during this phase to associated increases in stroke volume. The rapid improvement in the central circulation is explained by these authors as a result of rapid expansion of plasma volume. The expansion of plasma volume continued throughout their third phase of acclimation (days 4 to 6), which is characterized by increases in cardiac output. These authors further suggest that the plasma volume shrinks in the fourth phase (days 6 to 8) of acclimation.

The changes in blood and plasma volume seen in the present study should be discussed at three different levels: (1) the longitudinal changes during the acclimation process, (2) the daily changes caused by the exposure and (3) the differences between the summer and winter phases. As was expected from the previously published literature (8, 18, 21, 22), the daily differences between the pre- and post-exposure values in all the hematological parameters, except osmolality, were found to be significant. During the actual exposures, hemodilution was observed, as is evident by decreases in Hb, TP and ALB values, and increases in Δ PV and Δ BV. The blood volume increased due to plasma volume

expansion amd red cell shrinkage. Since changes in mean corpuscular volume can be estimated from changes in MCHC (7), the decrease in HCT and increase in MCHC values indicate that the cellular phase of the blood shrank during this same time period. The unchanged osmolality with decreased ALB and TP suggests that the expansion was due more to water and electrolytes shifting into the intravascular space rather than to protein shifts. These findings were also observed during the control days, both in summer and in winter. It can therefore be assumed that these changes were mainly exercise induced.

During both heat acclimation phases (W and S), the most extreme changes in hematological responses were observed in the middle of the acclimation period (sixth to eighth days). On these days, the highest hemodilution was observed (lowest Hb, HCT, MCHC, TP and highest Δ PV and Δ BV). In comparison to exercise induced hemodilution, the blood volume expansion of the winter acclimation occurred both in the plasma volume and in the volume of the cellular phase. In the latter type of hemodilution, particularly in winter experiments, most probably albumin was shifted into the vascular space. This suggestion is supported by the unchanged albumin level during the winter exposures, and by the smaller changes in albumin levels than the changes in plasma volume, or in total protein during the summer.

At the seasonal variation level, it seems that basically the same mechanism of blood volume expansion was involved both in summer and in winter. The main difference between the two seasons was the difference in the volume expansion between the two compartments of the blood, i.e., the plasma volume and the cellular phase. The following seasonal findings were observed: higher HCT values during the sixth day as compared to the first and the last day of acclimation in the winter and the opposite trend during the summer; greater

changes in MCHC in the winter (significantly higher values in winter for the first and last days of acclimation contrasted to the lower values for the sixth day); no differences in Δ BV and Hb between the two seasons; smaller changes in Δ PV and ALB in the winter than in the summer; and no differences in TP between seasons. This suggests that during the summer the main source of blood volume expansion is plasma volume expansion, while during the winter the cellular phase expanded more. Because this assumption is based on four independent variables (HB, HCT, ALB, TP), it can be assumed that these differences observed in the present study are more than coincidence.

In conclusion, after the summer season, the subjects were partially acclimatized to heat. This acclimatization was manifested by an unchanged T_{re} through a further period of acclimation to a more severe heat load. On the other hand, the cardiovascular adjustment to the heat, represented by HR, was not completed and further adaptation was achieved by acclimation. The mechanism involved in this added acclimation was mainly plasma volume expansion. In spite of 10 days of acclimation, the winter thermoregulatory set-point remained higher than in the summer. The latter, together with lower sweat rates after acclimation in the winter, seemed to represent the lower sweat sensitivity of the acclimated man in the winter season than in the summer. During winter acclimation the blood volume expansion was due to expansion both in the plasma and cellular phases, while in the summer the acclimation resulted in only plasma volume expansion.

ACKNOWLEDGEMENT

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TABLE 1. Comparison of rectal temperature (T_{re}), mean weighted skin temperature (T_{sk}), heart rate (HR) and sweat rate ($\dot{m}_{sw}$) (mean ± SE), during the two control days (C_1 and C_2), and the first, sixth and tenth days of acclimation (A_1, A_6, A_{10}) at the end of the summer (S) and the end of the winter (W).

							significance of differences			
		C_1	A_1	A_6	A_{10}	C_2	C_1-C_2	A_1-A_6	A_6-A_{10}	S – W
T_{re} °C	S	37.40 ± 0.11	37.63 ± 0.11	37.58 ± 0.11	37.61 ± 0.10	37.50 ± 0.06	NS	NS	NS	
	W	37.61 ± 0.07	37.98 ± 0.14	37.87 ± 0.06	37.76 ± 0.10	37.50 ± 0.06	NS	NS	NS	*
T_{sk} °C	S	30.3 ± 0.4	34.6 ± 0.4	34.4 ± 0.2	33.8 ± 0.2	30.8 ± 0.4	NS	NS	NS	
	W	31.2 ± 0.4	35.4 ± 0.5	34.7 ± 0.3	34.3 ± 0.3	31.0 ± 0.4	NS	NS	NS	NS
HR $b \cdot min^{-1}$	S	93.5 ± 3.5	123.9 ± 7.1	108.6 ± 3.1	117.1 ± 4.9	94.5 ± 2.9	NS	*	NS	
	W	95.4 ± 3.3	133.1 ± 8.0	114.9 ± 5.0	113.6 ± 5.6	90.0 ± 2.6	NS	*	NS	only on A_1
$\dot{m}_{sw}$ $g \cdot m^{-2} \cdot h^{-1}$	S	113.5 ± 18.6	334.8 ± 15.1	353.7 ± 21.8	350.0 ± 11.8	86.4 + 10.3	NS	NS	NS	
	W	94.3 ± 11.6	318.0 ± 16.8	310.7 ± 9.5	326.7 ± 16.3	86.4 ± 10.8	NS	NS	NS	*

* $P < 0.05$

a significant difference was found between A_1 and A_{10}

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TABLE 2. Comparison of hematological data (mean $\pm$SE) for the first control day (C), and first, sixth and tenth days of the acclimation period (A_1, A_6, A_{10}) at the end of summer (S) and end of winter (W) both pre and post-exposures.

		C_1 pre	C_1 post	A_1 pre	A_1 post	A_6 pre	A_6 post	A_{10} pre	A_{10} post	S-W	acclimation	pre-post
Hb g%	S	17.0 $\pm$ 0.4	17.7 $\pm$ 0.4	17.2 $\pm$ 0.3	16.7 $\pm$ 0.3	15.9 $\pm$ 0.2	15.5 $\pm$ 0.2	16.4 $\pm$ 0.3	16.1 $\pm$ 0.3	NS	$A_1>A_{10}>A_6$	*
	W	17.2 $\pm$ 0.6	16.2 $\pm$ 0.4	17.0 $\pm$ 0.4	16.8 $\pm$ 0.3	15.6 $\pm$ 0.4	15.2 $\pm$ 0.3	15.8 $\pm$ 0.4	15.6 $\pm$ 0.3			
HCT %	S	46.9 $\pm$ 1.0	45.4 $\pm$ 0.8	47.8 $\pm$ 0.7	45.4 $\pm$ 0.8	45.7 $\pm$ 0.6	43.7 $\pm$ 0.6	47.9 $\pm$ 0.8	45.4 $\pm$ 0.6	*EA_6	$A_6<A_1$&A_{10}	*
	W	46.2 $\pm$ 1.1	44.0 $\pm$ 1.0	45.2 $\pm$ 0.9	43.0 $\pm$ 0.9	46.3 $\pm$ 1.0	44.2 $\pm$ 1.3	45.1 $\pm$ 1.1	43.3 $\pm$ 0.9		NS	
ALB g%	S	4.67 $\pm$ 0.08	4.18 $\pm$ 0.10	4.56 $\pm$ 0.06	4.37 $\pm$ 0.07	4.24 $\pm$ 0.06	3.88 $\pm$ 0.07	4.50 $\pm$ 0.09	4.44 $\pm$ 0.09	*OA_6	$A_6<A_1$&A_{10}	*
	W	4.90 $\pm$ 0.07	4.66 $\pm$ 0.13	4.85 $\pm$ 0.07	4.66 $\pm$ 0.10	4.87 $\pm$ 0.08	4.62 $\pm$ 0.10	4.83 $\pm$ 0.12	4.60 $\pm$ 0.12		NS	
TP g%	S	7.86 $\pm$ 0.08	7.69 $\pm$ 0.09	7.78 $\pm$ 0.07	7.62 $\pm$ 0.08	7.36 $\pm$ 0.10	7.33 $\pm$ 0.06	7.74 $\pm$ 0.09	7.47 $\pm$ 0.05	NS	$A_6<A_1$&A_{10}	*
	W	7.76 $\pm$ 0.16	7.38 $\pm$ 0.09	7.75 $\pm$ 0.06	7.49 $\pm$ 0.05	7.53 $\pm$ 0.13	7.29 $\pm$ 0.10	7.61 $\pm$ 0.15	7.49 $\pm$ 0.10			
ΔPV %	S			base line	base line	3.1 $\pm$ 1.0	8.9 $\pm$ 0.9	-0.2 $\pm$ 0.7	5.5 $\pm$ 1.1	*OA_6	$A_6>A_1$&A_{10}	*
	W			base line	base line	-1.7 $\pm$ 0.7	4.5 $\pm$ 1.2	0.2 $\pm$ 0.9	4.3 $\pm$ 1.5		NS	
ΔBV %	S			base line	base line	7.6 $\pm$ 1.1	10.0 $\pm$ 0.8	4.7 $\pm$ 1.1	6.6 $\pm$ 1.0	NS	$A_1<A_{10}<A_6$	*
	W			base line	base line	7.9 $\pm$ 1.3	10.7 $\pm$ 0.9	7.0 $\pm$ 0.6	8.3 $\pm$ 1.1			
MCHC%	S	36.3 $\pm$ 0.5	39.0 $\pm$ 0.5	36.0 $\pm$ 0.4	36.9 $\pm$ 0.4	34.8 $\pm$ 0.4	35.4 $\pm$ 0.4	34.2 $\pm$ 0.4	35.4 $\pm$ 0.3	*	$A_1>A_6$&A_{10}	*
	W	37.2 $\pm$ 0.8	36.9 $\pm$ 0.7	37.7 $\pm$ 0.6	39.1 $\pm$ 0.6	33.8 $\pm$ 0.3	34.4 $\pm$ 0.5	35.1 $\pm$ 0.3	36.0 $\pm$ 0.4		$A_1>A_{10}>A_6$	
Osmolality $mOsm \cdot l^{-1}$	S	289 $\pm$ 3	287 $\pm$ 4	290 $\pm$ 2	289 $\pm$ 1	274 $\pm$ 2	268 $\pm$ 3	270 $\pm$ 2	273 $\pm$ 2	NS	$A_1>A_6$&A_{10}	NS
	W	273 $\pm$ 4	280 $\pm$ 4	276 $\pm$ 2	286 $\pm$ 2	283 $\pm$ 2	279 $\pm$ 1	287 $\pm$ 3	271 $\pm$ 5		NS	

In the significance of differences columns: * denotes $P<0.05$, E = except, O = only, $A_x> A_y$ = values of A_x are significantly ($P<0.05$) higher than those of A_y, S-W = difference between summer and winter, NS = not significant. Symbols in the middle space apply to both summer and winter.

FIGURE LEGENDS

FIG. 1. Final sweat rate ($\dot{m}_{sw}$), rectal temperature (T_{re}) and heart rate (HR) values during each day of the summer (solid lines) and the winter (dashed lines) exposures are displayed. The C_1 and C_2 are the two control days and 1-10 are the acclimation days.

FIG. 2. Final hemoglobin concentration during summer (solid lines) and winter (dashed lines) exposures with the pre- (open symbols) and post-exposure (closed symbols) values for the two control days (C_1 and C_2) and the ten acclimation days (1-10) are presented.

FIG. 3. MCHC during summer (solid lines) and winter (dashed lines) exposures are illustrated. Pre- (open symbols) and post-exposure (closed symbols) values for the two control days (C_1 and C_2) and the ten acclimation days (1-10) are shown.

FIG. 4. The changes in blood volume (whole blood and the cellular phase of the blood) during the summer (solid lines) and winter (dashed lines) exposures are given; pre-(open symbols) and post-exposure values (closed symbols) for the last control day (C_2) and the ten acclimation days (1-10) are shown. Pre-exposure values of the first acclimation day of each season are defined as 100% for the whole blood. The cellular phase values are the whole blood values multiplied by the hematocrit.

FIG. 5. Changes in plasma volume (Δ PV) during summer (solid lines) and winter (dashed lines) exposures are displayed. Pre- (open symbols) and post-exposures (closed symbols) values for the last control day (C_2) and the ten acclimation days (1-10) are shown. The pre-exposure values of the first day of both periods of acclimation are defined as Δ PV = 0 for that season.

FIG. 6. Plasma albumin concentration during summer (solid lines) and winter (dashed lines) exposures with pre- (open symbols) and post-exposure (closed symbols) values for the two control days (C_1 and C_2) and the ten acclimation days (1-10) are illustrated.

FIG. 7. Plasma total protein concentration during summer (solid lines) and winter (dashed lines) exposures with pre- (open symbols) and post-exposure (closed symbols) values for the two control days (C_1 and C_2) and the ten acclimation days (1-10) are illustrated.

1.	The views, opinions, and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other official documentation.

2.	Human subjects participated in these studies after giving their free and informed voluntary consent. Investigators adhered to AR 70-25 and USAMRDC Regulation 70-25 on Use of Volunteers in Research.
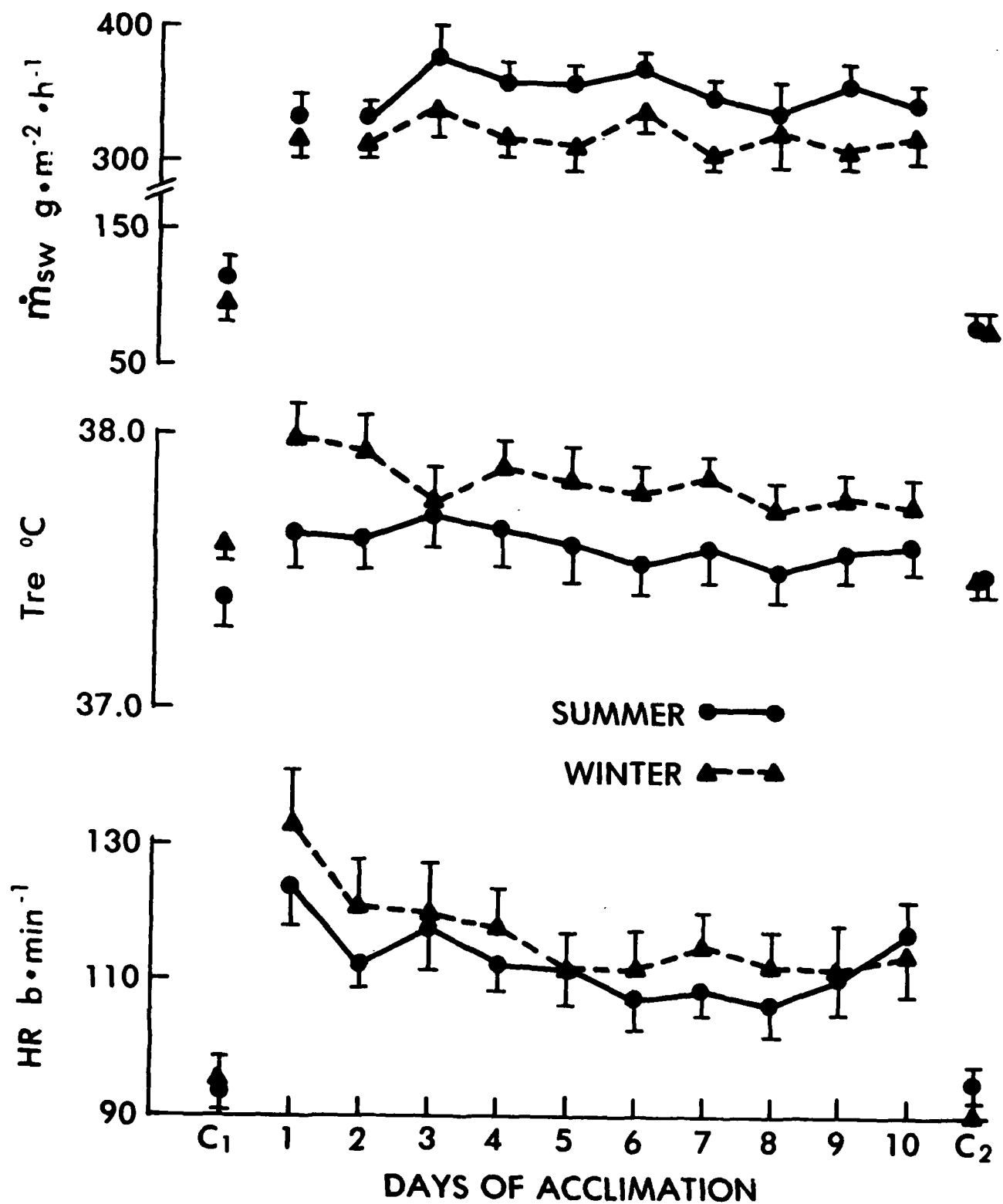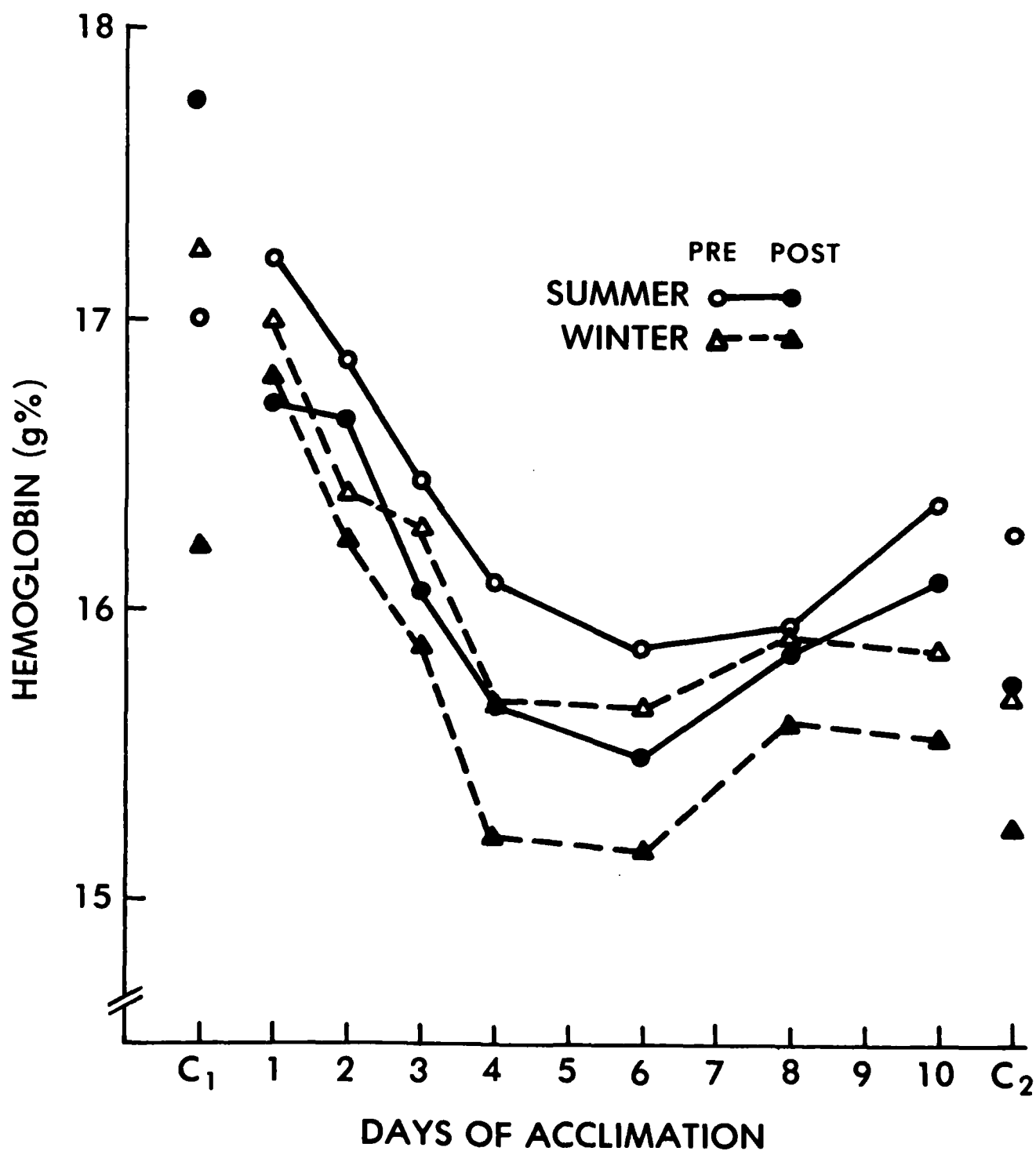
Figure 1 - Summer and Winter
acclimation to dry heat

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Figure 2 - Summer and Winter
acclimation to dry heat

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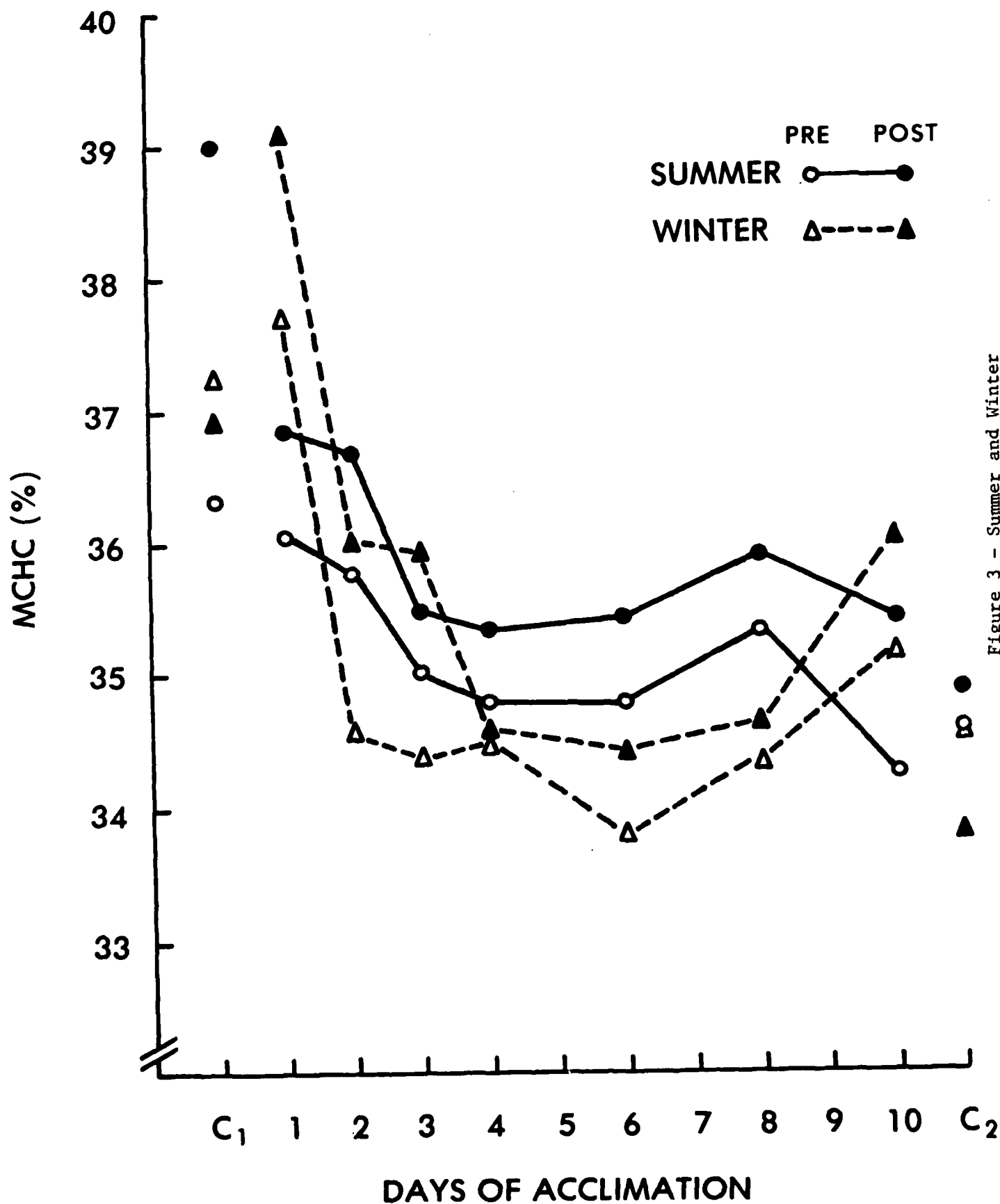
Figure 3 - Summer and Winter acclimation to dry heat
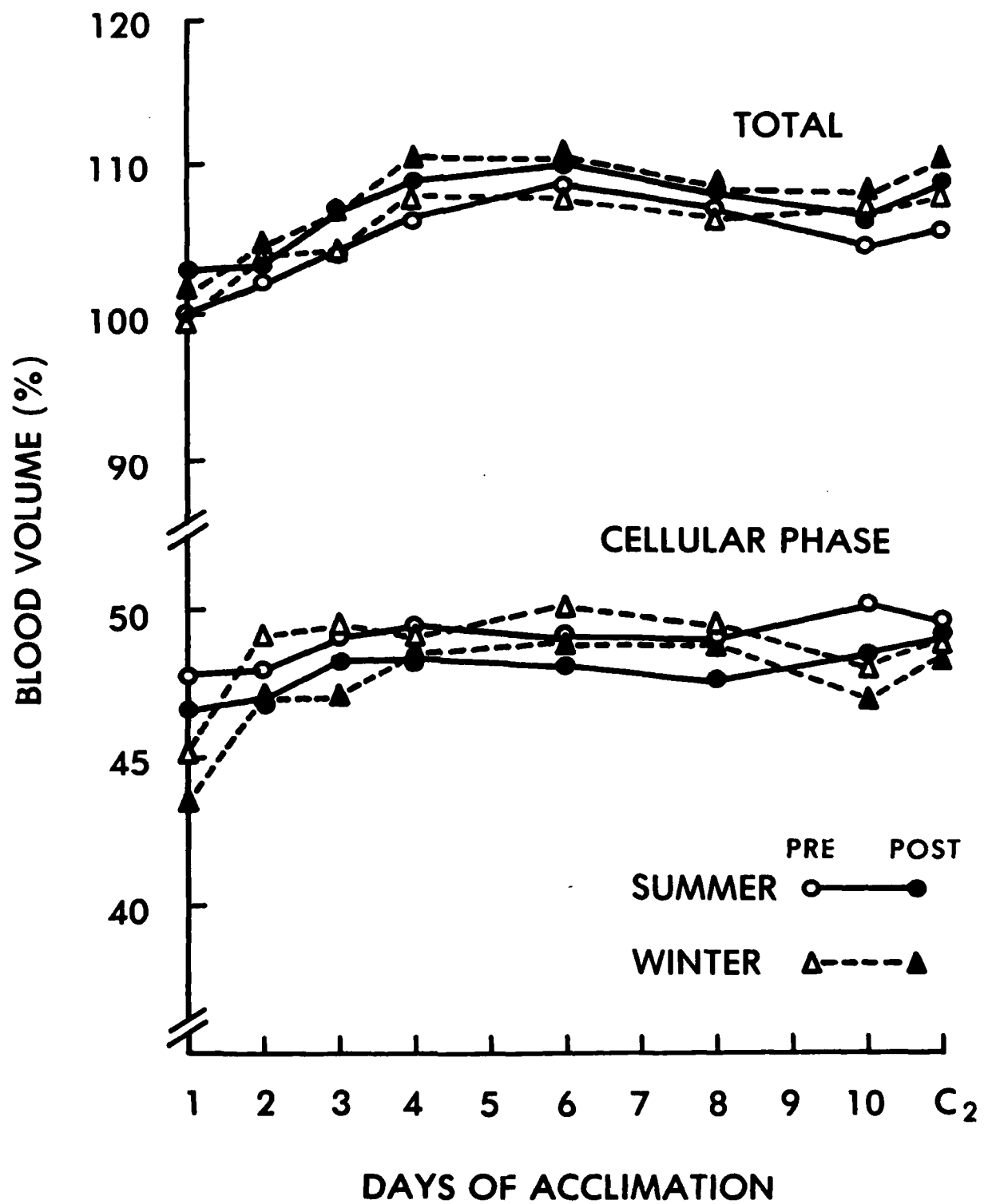
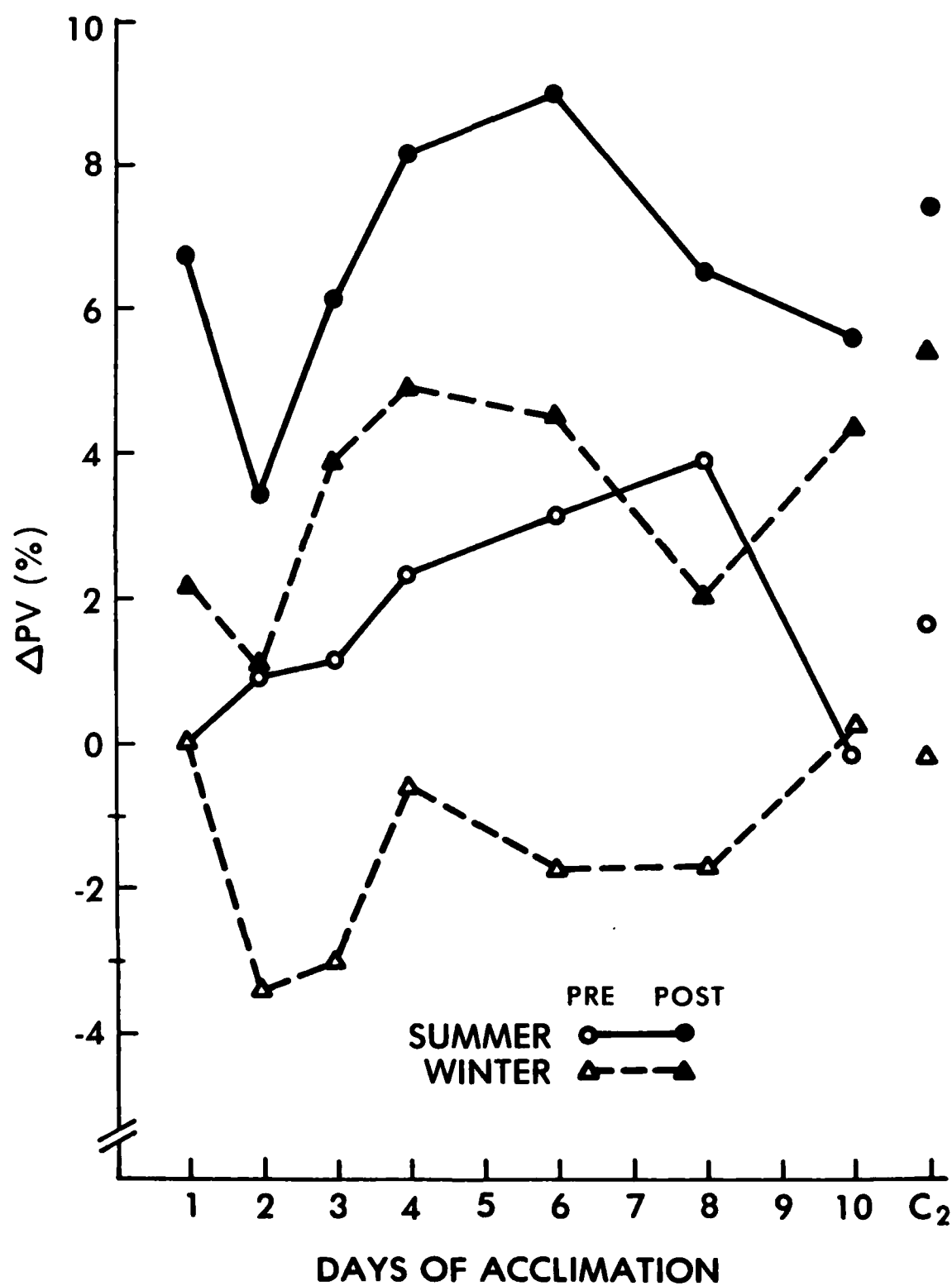Figure 4 – Summer and Winter
acclimation to dry heat

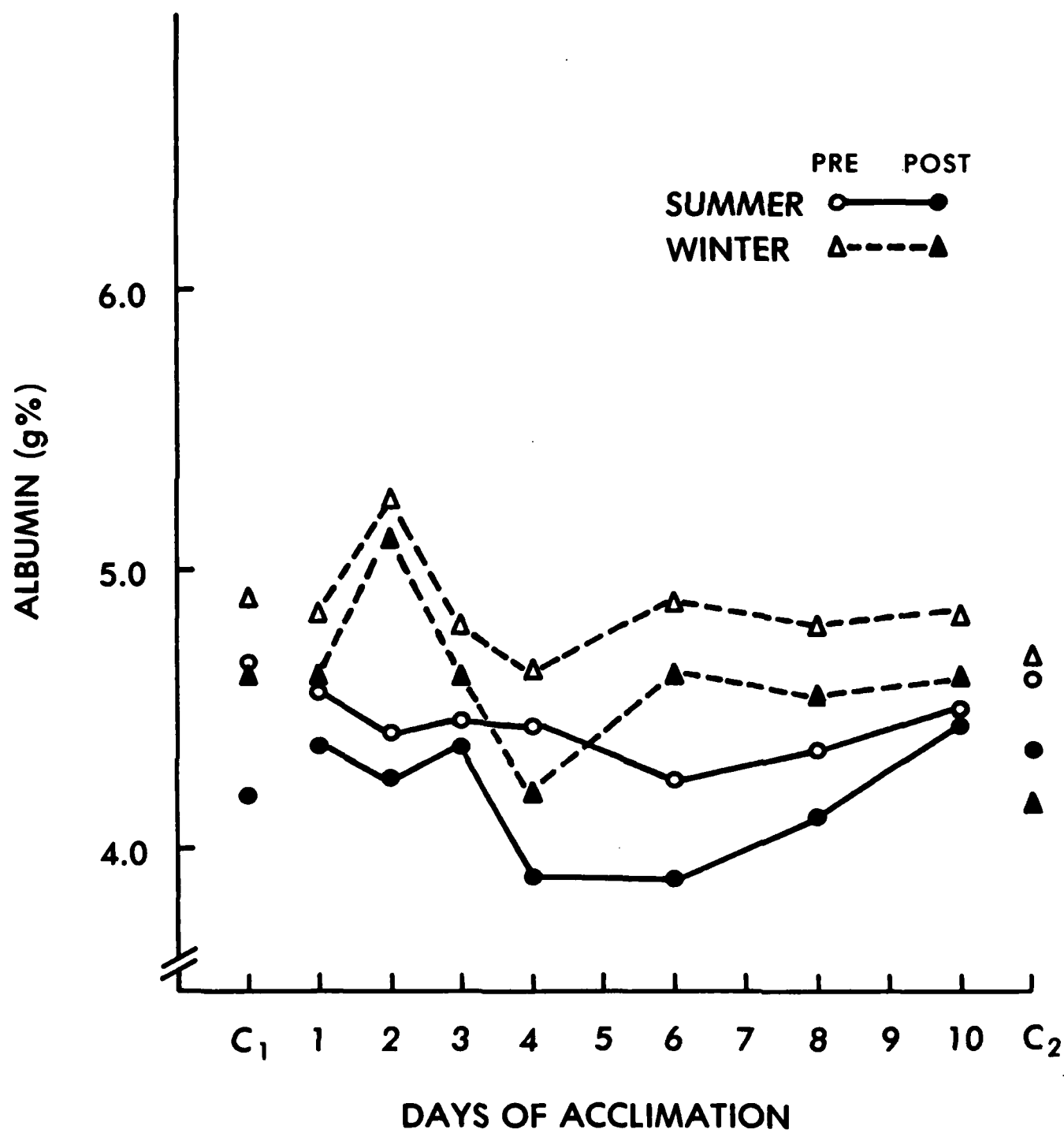Figure 5 – Summer and Winter acclimation to dry heat
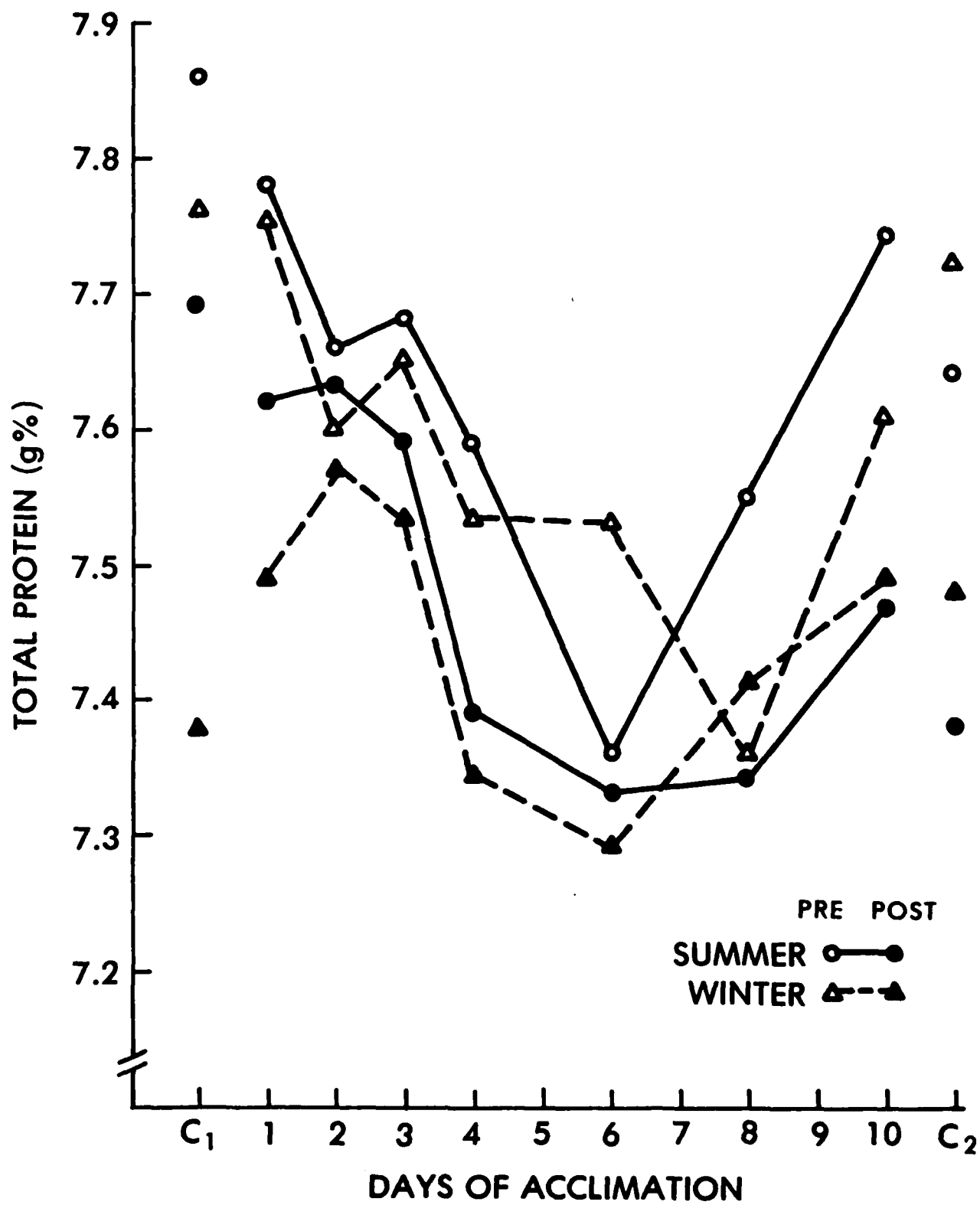
Figure 6 - Summer and Winter
acclimation to dry heat

Figure 7 - Summer and Winter
acclimation to dry heat

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